

Office of The Quartermaster General
Military Planning Division
Research and Development Branch

TEXTILE SERIES - REPORT NO. 61

THE RELATIONSHIP BETWEEN
THE STRUCTURAL GEOMETRY OF TEXTILE FABRICS
AND THEIR PHYSICAL PROPERTIES

PART II
ABRASION RESISTANCE

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

BY
STANLEY BACKER

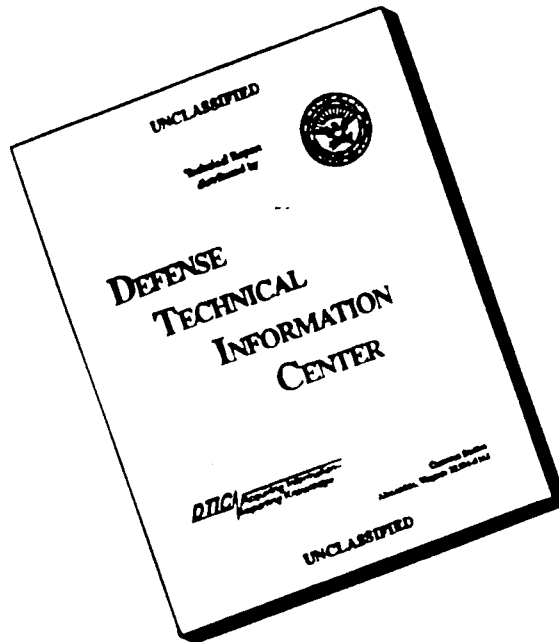
19960801 001

DTIC QUALITY INSPECTED 3

Released for public information
by
The Office of Technical Services
U. S. Department of Commerce

ATI NO. 151 938
ASTIA FILE COPY STI

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Office of The Quartermaster General
Military Planning Division
Research and Development Branch

TEXTILE SERIES - REPORT NO. 61

THE RELATIONSHIP BETWEEN
THE STRUCTURAL GEOMETRY OF TEXTILE FABRICS
AND THEIR PHYSICAL PROPERTIES

PART II
ABRASION RESISTANCE

by
Stanley Backer

Released for Public Information
by
The Office of Technical Services
U. S. Department of Commerce

FOREWORD

During the war both in Germany and in this country, increasing attention was given as the war progressed to problems of serviceability of textile materials. With the Germans the problem was one of utilizing synthetic materials of less general serviceability than some of the natural materials which had been available in peacetime, and, more important, attempting to attain the highest possible efficiency of a limited industrial capacity, so as to relieve the pressure upon the economy in meeting both military and civilian requirements. As a result a great deal of study was undertaken in the field of fabric serviceability, and some quite worthwhile progress made in the direction of comprehensive understanding of the problem. A collection of the more important war-time German publications on the serviceability of textiles has been published in English translation by Melliand, and will shortly become available to technicians in this country through the U. S. Department of Commerce.

In this country the pressure upon our industrial capacity did not become critical until the latter part of 1944, although prior to that time increasing concern had begun to be felt with respect to the enormous requirements for textiles which apparently were needed in large part because of their relatively limited service life.

The studies which were initiated toward the end of the war soon made it clear that a systematic study of the factors affecting wear, in terms of fabric structure, would have to be investigated before any genuine progress could be made in this direction. Out of the work which was initiated at that time by Mr. Backer and his associates has come an approach to the improvement of military textiles based upon knowledge of basic fiber properties and the form in which such properties become modified in the process of manufacture of the textile material.

This report, which is the second in a general series by Mr. Backer on structural geometry of textile fabrics, surveys the field of friction and wear of solids, and attempts to apply these principles to the problem of abrasion of woven cloth. The report also presents a summary of the applied work carried on by the Quartermaster Corps during this period. A previous report, Textile Series No. 52, represented a literature review of this field. It is believed that the information contained in this report will be of a great deal of interest to those who are taking a fundamental view of textile structures and their mechanical properties as the basis for designing textile fabrics with predetermined physical characteristics.

While a great many different individuals contributed to this work, which has been under the direction of Mr. Backer, special reference should be made to the great assistance which the Quarter-master Board has given to our office in all of these investigations, by providing a field evaluation center which could serve as a norm for the study of textile serviceability. The continued cooperation and interest of the Board in this project has been invaluable, and it is believed will ultimately be found to have formed one of the most important contributions to the understanding of service life of textiles.

In addition, I should like also to make special mention of the work of Mr. S. J. Tanenhaus, who during the post-war period has served as the leader of the project on Wear Resistance of Textiles.

S. J. KENNEDY
Research Director
For
Textiles, Clothing and Footwear

September 1949

TABLE OF CONTENTS

	Page
Introduction and Summary	1
Conditions Affecting Friction and Wear	10
Pressure	10
Tension	14
Speed of Rubbing	15
Surface Temperatures	17
Presence of Moisture	19
Evaluation of Damage	20
Material Properties Affecting Friction and Wear	22
Surface Characteristics	22
Lubrication	28
Mechanical Properties	30
Change of Surface and Material Properties During Wear	37
Contribution of Textile Geometry	41
Influence on Pressure	41
Threads per Inch	41
Yarn Diameters	44
Crimp Distribution	49
Weave versus Projection	53
Twist versus Contact Area	60
Direction of Abrasion	62
As Related to Yarns	62
As Related to Fibers	64
As Related to Molecular Orientation	65
Compliance	67
As Related to Compressional Properties	67
As Related to Fabric Tightness	68
Conclusion	73
Acknowledgements	74
Bibliography	75
Appendices	92

INTRODUCTION AND SUMMARY

Textile materials used by the armed forces are subjected to severe treatment in service and are known to fail in a number of ways due to chemical, photochemical, microbiological and mechanical factors. (3,8,35,47,60,67,69,89,177,197,205,206,102,178,181,207,214) Before the extensive tropical operations of World War II introduced photochemical and microbiological degradation as prime factors leading to early loss of utility of our textile products, the major source of fabric failure was mechanical in nature. Included in the mechanical category are the following elements: tensile stress; flexing; compression; puncture; shear; dimensional instability due to the above actions, to laundering or to yarn slippage; snagging of yarns; and surface rubbing. (45,60,169,177,213)

While all of the above factors influence the wear life of textiles, it is usually the latter item of surface rubbing that is implied in the term wear resistance. Such misuse of terminology has some justification in the fact that with recent improvements in the tenacity of regenerated and synthetic fibers, shrinkage treatments to reduce dimensional instability, and resin finishes to eliminate yarn slippage, surface abrasion remains as the major factor which determines the duration of end item utility.

As applied to continuous solid materials, abrasion has been defined as the process of wearing away the surface layers by doing work on the surface. (211) The amount of work done during abrasion depends upon the frictional resistance which the solid exerts when rubbed against another object. (41) It follows that the ability of a material to return energy absorbed during surface rubbing is a controlling factor in establishing the abrasion resistance of the material.

It is well recognized that textile fabrics are not homogeneous isotropic materials. Instead, woven cloth represents a combined volume of air and fiber, wherein each fiber, anisotropic in nature, and of a length which is several thousand times its diameter, is helically twisted into a cylinder of varying hardness with other rod-like fibers which differ in length, diameter, cross section, and morphology. The twisted structures are then laid in a horizontal plane with other yarns and perpendicularly interlaced with a group of similarly constructed parallelized cylinders in numerous combinations and permutations of cylinder diameters, spacings, and manners of interlacing. In short, every conceivable factor of orientation and solid geometry has been introduced to ensure that the fabric does not behave like the material of which it is chemically constituted. It is through such repeated application

of geometry, starting with the tailoring of the molecule⁽¹²⁵⁾ that textile science can achieve products so variable in appearance, beauty, comfort, and utility, embracing untold subtle difference in character and properties.

It is therefore logical that abrasion performance of solids be used only as a starting point in investigating the complexities of the mechanical attrition of fabrics which occurs through rubbing. Such studies carried out on solid materials emphasize the importance of the frictional phenomena. Numerous references are made to the well known law that the frictional force, F , required to slide two surfaces in contact by one another is proportional to the total load, P , pressing the surfaces together. This relationship has been attributed to either the adhesion⁽¹⁸⁹⁾ between points of real contact or to the roughness of the solid surfaces. Considerable data have been reported during the years succeeding Coulombs⁽⁴²⁾ to establish the significance of one or the other cause,⁽¹²⁾ but it is reasonable to assume that the nature of the experiment and the character of the materials studied⁽⁵⁷⁾ determine the importance of each of these two factors.

Whatever the causes for frictional resistance it is important to note the effect of frictional energy and its dissipation. The view generally held⁽¹⁵⁰⁾ with regard to avenues of dissipation of this energy (frictional force \times distance) is: (1) transformation into thermal energy immediately or upon recovery of the elastic strains incurred during rubbing, (2) increase in the internal energy of the surface as a result of cold working with subsequent slow release of thermal energy upon recrystallization, and (3) increase in the surface energy of particles torn from the surfaces of the solid - this energy is not transformed into heat.

The relative importance of each of these phases depends upon the indigenous character of the material, its geometric form, and the conditions of its abrasion. Except for the degrading effects of the heat developed during or after rubbing and changes in surface properties due to cold working, it may be expected that the third avenue of release for frictional energy is most closely associated with abrasion damage. It follows that increases in frictional energy during surface rubbing will normally promote greater wear damage, but the relationship between such attrition and the energy function is not a simple one. Indeed in certain instances it has been observed to assume an inverse character.⁽⁴⁷⁾

In this paper frictional resistance between surfaces is associated with abrasion damage, and factors which affect both phenomena are studied together. In the majority of the cases observed parallel effects are noted. In several instances where anomalies have been reported secondary agents have been shown to predominate the scene, thus out-

weighing the original relationship. In the few remaining anomalies sufficient data have not been reported to permit close scrutiny of the interactions between opposing factors. Among the conditions discussed are: pressure and tension on the materials being rubbed, speed of rubbing, surface temperatures and moisture content, and evaluation of damage. Without knowledge of the surface and mass properties of the rubbing materials, it would be impossible to draw a complete picture of the significant factors in friction and wear. A section of the paper is therefore devoted to a discussion of surface roughness, lubrication, mechanical properties of the solid, and change in surface and material properties during wear.

This treatment provides a firm foundation for consideration of the contribution of textile geometry to the abrasion performance of woven fabrics. Added to the causative agents of the mechanical attrition of solids are the translational effects promoted by the molecular, fibrillar, fiber, yarn and fabric geometry peculiar to textile structures. To deal exhaustively with this latter phase would require the concentrated efforts of a large staff over a period of years. To furnish stimulus for such a program there are reported here the results of numerous Quartermaster experiments, each of which has been planned with a limited applied objective. It is nevertheless hoped that the isolated nature of the tests reported may be overcome in an integrated presentation and that the investigations reported may be extrapolated by the reader to cover new combinations of wear conditions and textile structures.

In the discussion of pressures it is shown that as normal loads between rubbing surfaces are increased, greater damage takes place. Whether in consideration of elastic metallic solids or of visco-elastic substances the general trend is consistent. However, quantitative differences exist in the treatment of the two types of material. Friction between nonlubricated metals is dependent on area of true contact and on shear strength. True area of contact is independent of geometric area of contact for metals but is directly affected by normal loads. Friction between a visco-elastic substance and a solid surface, however, is dependent on pressure and geometric area of contact, for with relatively soft, compressible surfaces there is an interrelationship of normal load, geometric area, true pressure, and true area of contact. It follows that the wear damage of visco-elastic textile fabrics may be minimized by increasing the geometric area of contact and reducing the normal loads at local points.

Fabric tension has an effect on the abrasion life of textiles when distortion of the surface results. In most cases, however, tensions incurred during laboratory or field wear significantly affect surface characteristics only in the late stages of destruction, as the material is abraded to rupture of the yarn systems.

While speed of rubbing cannot be controlled in service, it is prominent among the laboratory test factors which may be varied at will. Nonlubricated metals generally absorb less frictional energy at higher speeds of rubbing due to reduction in the areas of flow, the points of welding and consequently the forces required to rupture the welds. Lubricated metals, however, have higher frictional coefficients at increased speeds of rubbing as a result of increased viscous shear resistance in the lubricant. In most cases textile materials have higher coefficients of friction and higher abrasion rates at increased speeds of rubbing, due in part to the stiffening of their structures at higher rates of strain and absorption of greater frictional and abrasive energies.

Surface temperature during rubbing is important in that it affects the physical properties of the lubricants and the rubbing bodies. Temperatures incurred will depend upon load, speed, coefficient of friction and thermal conductivity of the masses. At higher temperatures the viscosity of lubricants and films is reduced, resulting in lower shear resistance and coefficients of friction for both metals and textiles. However, local flashes and over-all generation of high temperatures due to poor heat dissipation may at times markedly alter the surface properties of metals so as to increase true contact and flow areas and thus boost frictional resistance and abrasion damage. In the case of textile materials the significant influence of a lower range of temperatures on the fiber properties must be considered. Finally, the importance of slight amounts of heat to accelerate relaxation of surface strains is noted.

Moisture is a variable factor in abrasion and friction tests. Adsorbed films of moisture significantly reduce friction between otherwise clean metal surfaces. However, excesses of moisture on normally contaminated surfaces have been observed to increase friction and even introduce an adhesive characteristic. In the case of native and regenerated cellulose and protein fibers, the surface effect is negligible compared to the complete modification of the physical properties of the high polymer as a result of the presence of moisture. However, this dependence varies in sign with different fibers. It is expected that fibers for which increased moisture content imparts higher strength and lower elastic modulus, will wear better in the presence of moisture and vice versa.

Numerous methods of evaluating fabric wear damage have been proposed in the past. These include change in strength, weight, air resistance, modulus of elasticity, dielectric constant, color, appearance, and thickness; or formation of holes. It is felt that the ideal method is that which permits nondestructive study of the progressive change of a single character of the material during wear. However, the end point designated for such a method must correspond with loss in

utility during service. Despite its destructive nature progressive strength loss is preferred as a measure of wear although considerable promise exists for the newly developed sound-modulus and capacitance methods.

Classical laws of friction have been based upon two major premises, (1) that of interlocking surface projections and valleys and (2) that of molecular attraction at isolated points of real contact. Where complete lubrication is achieved (with negligible viscosity) it has been shown that the coefficient of friction becomes a function of the average slope of the surface projections, that is, directly related to surface roughness. The surface roughness of textiles is a composite quantity starting with the scale-like structure of hair fibers, the convolutions of cotton or the fibrils of rayons, and encompassing fiber twist and parallelization, yarn diameter uniformity and cloth weave. Here roughness becomes more difficult to evaluate quantitatively. The matter is discussed at length in reference to fiber, yarn, and fabric geometry. It is concluded that abrasion resistance can be increased by reducing surface roughness to a point consistent with the optimum levels of other interacting properties.

It is shown that the nature of the abradant is to a major degree responsible for the character of fabric attrition, that is whether gradual or sudden, partial or complete disintegration of the individual fiber, or direct breakdown of the yarn structure through fiber snagging. Finer abrasives and smoother rubbing surfaces are responsible for the first type of breakdown, while extremely coarse surfaces cause fiber snagging resulting in loss of fabric cohesion. Fabric structure and direction of abrasion are ever-present interacting agents in determining the nature of breakdown to be expected. It remains to study the characteristics of the abrasive surfaces encountered in actual wear and to attempt their simulation in the laboratory.

Lubrication is considered as a key factor in friction and wear of rubbing surfaces. Clean surface contact is rarely met in service and can therefore be discounted except where breakdown in boundary lubrication occurs. At this point tremendous adhesive forces come into play and intermittent welding and weld rupture takes place. In service wear of metals a condition of hydrodynamic lubrication is sought in which all shear takes place within the lubricant and the solid surfaces suffer little damage. In textile wear the condition of boundary lubrication is usually achieved, accompanied by occasional breakdown under varied conditions. Here both physical properties of lubricant and solid take part and together with surface roughness determine the extent of damage incurred in rubbing.

Mechanical properties of the solids are often shown to affect surface rubbing phenomena under normal conditions of wear. During the initial approach of solid surfaces material hardness determines the extent of true contact which will exist for corresponding normal loads. The shear resistance of the material comes into consideration, for it is seen that the integrated products of projection area and shear strength determine the resistance to relative parallel motion between the surfaces. A point which is stressed in the studies reviewed is the need to consider these material properties at the surface temperatures developed during wear. It is concluded that while shear resistance and softness are key properties in wear of metals, the textile picture is further complicated by those properties which lend mobility to the fiber and yarn structure, for example, low modulus of tensile elasticity and a large immediate elastic deflection. The order of abrasion resistance of commercial fibers is given.

It is manifest that any change in the properties of surfaces or solids during wear will modify the rate of abrasion. Cases are cited where formation of films, dulling of edges, transfer of materials, surface strain, and temperature effects, singly or in combination, alter the frictional character and the abrasion performance of metals and textiles. There is no consistent trend in this effect because of the numerous conditions of exposure reported. It remains essential to regard critically the character of the surfaces and the nature of the modification before drawing conclusions as to the change in abrasion rate which may be expected. In many abrasion tests it may be possible to eliminate most of the difficulty by continuously cleaning or renewing the abradant surface, but it must be remembered that during such tests the specimen surface will also change.

Possibilities of improving the wear resistance of textiles are discussed in the section on The Contribution of Textile Geometry. One of the first steps which may be taken is the reduction of normal load in the individual elements of the textile structure. It has been pointed out that true contact areas of pliable visco-elastic substances are related to geometric contact areas. Therefore, by increasing the latter one can reduce unit load directly. One of the practical means which have been illustrated to improve wear life in this manner is through an increase in the number of units per inch in the yarn system which projects at the rubbing surface. Further, it may be demonstrated geometrically and empirically that increased yarn diameters will provide greater area of surface contact and correspondingly reduced pressures. The effect of higher diameter yarns on abrasion rate is demonstrated in monofilament yarns. It is also indicated that increased cross-yarn (nonprojecting) diameters will greatly reduce crown wear. The relationships between geometric contact areas and yarn diameters at various stages of abrasive attrition are developed by use of mechanical models.

Crimp distribution is considered as it influences yarn projection and therefore contact areas. An expression is developed for true crimp at the unit cell as opposed to measured crimp. Investigations of crimp effect on abrasion are reviewed and photographs are furnished to illustrate the geometry which prevails in selected fabrics. It is concluded that geometric planning must take into account relative yarn diameters and frequency as well as yarn stiffness and finishing methods in order to ensure matched projection of both yarn systems, or where desired for reasons discussed, unbalanced but controlled projection at the rubbing surface.

Weave is presented as another factor which markedly influences yarn projection and therefore contact areas at the rubbing surface. Uniformity of weave pattern and the avoidance of breaks in the design which result in isolated yarn projection, as in the case of herringbone twills, are desired. Longer floats generally predominate at the surface whatever the crimp distribution. This comes about as a result of the arching of the float for lack of plane restriction. The amount of projection is related to float length. This aspect is a deterrent to wear life when the long floats appearing on the fabric surface which is subject to abrasion consist of the load-bearing yarns. Conversely, it is a direct boon when the opposite system of threads appear on this surface, thus protecting the yarns carrying the major portion of the tensile stress. The high wear resistance of the warp sateens worn filling flush in Army experiments is attributed to this feature.

The role of yarn twist in fabric wear is reviewed and the similarity observed between abrasion-twist curves and strength-twist curves. For it is manifest that yarn structure hardness and in the case of spun yarns, cohesion, is dependent on a moderate amount of twist. Such twist serves to reduce snagging and early breakdown of yarn cohesion in wear. However, excess twists are seen to prevent crown flattening and reduction in local abrasive pressure and, because of the greater helix angle involved, contribute more heavily to loss of yarn strength at a given depth of crown attrition.

Observed in the early studies of cloth abrasion was the effect of direction of rubbing upon the damage to projecting yarns. Generally, projecting yarns suffer maximum damage when abraded perpendicular to their float length. It follows that greater wear efficiency is had in those fabrics subjected to abrasion in one direction and stresses at right angles, for here the fabric can be designed with non-stress-bearing floats projecting at the rubbing surface and lying in the direction of wear. It is demonstrated that cross-float abrasion tends to produce fiber snagging and loss of yarn cohesion rather than shearing of individual filaments. Yarn curvature at the point of contact is also discussed and it is shown that maximum damage from cross-

float abrasion is indicated from geometric considerations of curvature.

Similar reasoning is extended to include the direction of fibers as they lie in the yarn but here experimental evidence is scarce and more work is indicated. Nor is the discussion limited to macroscopic properties, for molecular orientation bears an important relationship to the direction of abrasion, as all textile fibers are characterized by high orientation along their axis and therefore at reasonably high tenacities it may be expected that local stresses occurring in a direction perpendicular to the axis will introduce untold complications. Analysis of the mechanism of abrasion of cloth structure presents the picture of an abradant particle approaching the surface fiber from such a direction as to furnish axial and perpendicular stress components. The relative magnitude of each component will depend on the angle of approach, the abradant surface, the relative speed, the fiber diameter and the fiber surface. In instances where the major component is axial, the tensile properties of the fiber will predominate. Where the tangential component is of significant magnitude the shear strength of the fiber enters the picture. It is seen that low tensile modulus will assist the fiber in relieving shear concentrations. Calculation of an arbitrary ratio of the square of shear strength to initial tensile modulus of the fiber showed rough correlation with reported values of abrasion resistance of the fibers. It is concluded that ratios of this type are particular in nature, applying to specific conditions of abrasion and must be altered to fit the nature of wear and the structure of yarn and fabric.

Compliance which favors longer wear life can be obtained in many ways, one of the most manifest of which is to increase the compressibility of the fabric structure. Here, material properties, fabric structure and thickness, and backing material are shown to play a significant role. Compliance may also be achieved through reduction in fabric tightness. Expressed in terms of yarns, tightness can be reduced and compliance improved with longer float lengths. It is shown that excess shear stress and high transmittal of tensile stress may be avoided through translational compliance at contact points as enhanced by increasing yarn radius and float length and decreasing fiber twist and tensile modulus. In terms of the fabric, compliance is seen to be dependent on cover factors and weave. Expressions for cover factor tightness are demonstrated for plain weaves and correction factors developed to include other weaves. It is concluded that improved wear may be expected when maximum surface translation compliance is achieved consistent with yarn and fabric cohesion. Finally, the application of these principles in the improvement of the wear life of Army fabrics is demonstrated.

In conclusion, it may be stated that this paper is directed towards a clarification of the significant factors in laboratory and

service abrasion tests and the contribution of fabric geometry in increasing cloth durability. It seeks to point out the elements in our present-day standard laboratory abrasion tests which lead to anomalous results. Finally, it is hoped that the systematic discussion of geometric factors in abrasive deterioration will form a foundation of principles upon which improvement of utility fabrics for military and civilian wear can be based.

CONDITIONS AFFECTING FRICTION AND WEAR

PRESSURE

Going back to some of the earliest work in friction, one finds a statement of hypothesis⁽⁸⁰⁾ that small irregularities of surface of two solids in contact interlock and either elastically deform or abrade each other during relative motion. The tangential force required to effect such motion is the friction force^(2,42,208) and is found to be proportional to the normal load between the materials over wide ranges of velocity and load. Assuming clean surface contact, it follows that as the pressure between specimens increases, so does the frictional force and with it the abrasive action between the surfaces.⁽¹²³⁾ Pressure between surfaces is thus an important factor influencing the abrasion life of solids.⁽¹⁴⁹⁾ In measuring pressure in abrasion testers one must account for all the forces acting on the fabric since normal rubbing pressure is on occasions applied through fabric tensions. This is the case in all instruments where the fabric specimen is not backed with a solid material but develops force vectors through sample tensions.^(18,44,103,158,176) In such cases, fabric tension must be resolved into the pressure element exerted normally against the abradant and combined with the directly applied normal force.

The effect of such normal pressure on abrasion resistance has been studied on a number of instruments^(47,75,158) and the general relationship cited below has been developed for various textile materials:^(44,103,147,166,169,171,172,176,184,220)

$$C = KP^{-k},$$

where C is the number of cycles to end point, either reported directly, or in units of time for constant velocity of abrasion or frequency of oscillation; K and k are constants; and P is the load per unit area of the specimen given directly or computed from specimen tensions. While values reported for K and k were different for these various investigations, the relationship follows that often reported in the literature for solids.^(150,199)

In actual wear testing the load between abrasive and specimen actually fluctuates significantly during test, particularly in the reciprocating type machines. The extent of this oscillation will depend upon the smoothness of operation of the wear tester,⁽⁴⁵⁾ and a high degree of fluctuation will aggravate points of local wear.⁽²¹⁰⁾

The simple laws of friction establish that the load applied by one surface upon another is directly related to the frictional force

required to impart relative motion between the two solids, although the condition of the surfaces often introduces anomalies in experimental data to modify the relationship. It is known that there are three types of friction: (1) that caused by perfectly clean solid surfaces rubbing against one another resulting in seizure and welding due to unsatisfied molecular attractions extending a few Å from the surfaces and acting at a relatively small number of points of contact between the solids(1,12,18,27,189) (frictional coefficients under these conditions often approach 5 to 6); (2) boundary friction where the surfaces are separated by a monomolecular layer or film (10^{-8} cm. or more) which reduces the interacting attractive forces at the surfaces by preventing close approach of projections or rough spots of the two solids;(1,7,9,10,12,18,20,24,26,34,57,74,86,156); (3) hydrodynamic friction where surface films or layers of low shear strength materials are built up above 5×10^{-4} cm., and for the most part, prevent contact between surfaces. Fortunately adsorbed gases (in particular, oxygen) and surface contaminants(159,162,163,202) prevent the occurrence of the first type of friction. If this were not the case such friction would be a serious deterrent to high speeds and long life in mechanical items, for upon second thought, it becomes evident that friction is involved in all motion.

In the case of boundary lubrication, which we shall consider hereafter as the normal condition of friction and abrasion, the friction force is noted to be a linear function of applied load.(10,86) Contradictions to the direct relationship between tangential force and normal load have been oftentimes reported for conditions where a combination of friction types is present. This has been clearly demonstrated in the case of sliding friction under extreme pressures(50) where increases in the frictional coefficient occurred with increasing loads in a specified range of velocity and decrease has occurred at velocities above and below this range. Similar phenomena have been reported in studies of friction between lubricated surfaces,(34,116) but these will be discussed in the later considerations of the effect of velocities.

The relationship between pressure and load brings to mind a question as to whether area should not play a part in frictional relationships, in that increasing the geometric area between surfaces with constant load should reduce the pressure over each square inch, i.e., the load per square inch of contact surface. This should result in a reduction in the tangential force required to introduce or maintain motion between contact points. If the reduction in tangential force per unit area is proportional to the pressure (Coulomb's law applies) the integration of tangential force necessary to introduce movement between surfaces will remain constant with the total load. In the case of metals, however, it has been shown that increase in geometrical area of contact does not increase the number of contact points, but merely distributes them over

a greater area.(1,12,27,31) Increases in loads between the surfaces on the other hand create excessively high pressures at few points of contact causing flow and increase in contact area until the ratio between load and true contact area reaches equilibrium with the resistance of the stressed contact points to further deformation. To a first degree of approximation(57)

$$N = AH,$$

where N is the normal load on the plane of the contact region of the surfaces, A the projection of the area of true contact on the plane of the contact region, and H the pressure surface hardness value for the softer of the two surfaces.

In the absence of lubrication these points of high contact pressure will adhere or weld. Subsequent sliding causes a shearing of these welds, damage to both surfaces whether polished or rough, and transfer of matter.(1,19,34,57,150,156,208) Measurement of real contact areas of touching metals (through electrical resistances) has shown contact to be proportional to pressure. If the strains set up in this manner do not exceed the elastic limit of the material, it may be expected that removal of the normal load will reduce the area of true contact proportionately.(57) In practice, however, some hysteresis of contact area vs. load has been noted,(6,27) and friction forces have been observed to vary with the history of loading prior to movement.(83,146)

In studies of electrical contacts between metals it has been shown that actual contact area is independent of the geometrical or apparent area of contact and that the conductance at two surfaces is proportional to the load. Here, too, there is shown a hysteresis effect with repeated applications of load wherein the reciprocal of the electrical resistance, $1/R$, does not resume its original value, and in cycling between two loads, $1/R$ at the lower load increases with successive cycles until it equals $1/R$ at the higher load and no further change in conductance is noted. After many variations in load, the area of true contact levels off at a point proportional to the peak load incurred, representing a condition of plastic flow of the projections of the two surfaces.(12) In visco-elastic materials early flow may be expected at relatively low loads with the result that larger true contact areas are formed, say between a textile fabric and the surface of a solid, reported to be approximately 18 to 20 per cent of its general area.(94) Increase in contact area under such conditions will accordingly lessen the contact pressure at local points and in this manner influence the tangential forces required to impart motion. The complex nature of the interaction disrupts(32,51,146,148,181) the simple relationship described by Coulomb, and introduces an area function as indicated below:(98)

$$F = \mu_o P + kA, \quad \text{or} \quad \frac{F}{P} = \mu = \mu_o + \frac{kA}{P}, \quad \text{or} \quad \frac{F}{A} = \mu_o \frac{P}{A} + k = f_t,$$

where F is the total tangential force required to move a textile surface across a given solid, P is the total normal load, A is the contact area, μ_0 is the real frictional coefficient also termed the increment frictional coefficient,⁽³⁴⁾ μ is the measured coefficient, k is a constant,^(51,69,98,107,117) and f_t is the tangential force per unit of contact area. The nature of local attrition is determined by the amount of the frictional energy absorbed locally and therefore by the magnitude of f_t . It is evident in the above relationship that an increase in area of contact with constant normal load should reduce the extent of wear damage. This is borne out in later discussions of fabric geometry. The difficulty which arises in friction and wear studies is, of course, the determination of true contact area, for A will vary nonlinearly with P in many visco-elastic structures. Textile fabrics have very uneven surfaces due to the interlacing of yarns and the twisting of fibers. The fibers themselves have irregular surfaces which complicate friction measurements from the standpoint of contact area,⁽¹⁸¹⁾ and in the case of wool, projecting scales.^(97,98) The directional friction effect, D.F.E., of wool fibers is often attributed to this scalelike structure although considerable evidence has been presented⁽¹⁰²⁾ to vitiate this concept. Instead it has been postulated that materials which demonstrate a D.F.E. are polar in nature and differ in surface molecular behavior depending on direction of rubbing. Surface irregularities can be detected at optical microscopic magnifications in the case of natural fibers,^(39,105) while more recent work with the electron microscope has revealed the irregular surface of the "smoother" synthetic fibers.⁽⁸¹⁾ Additional precautions must be taken in reporting friction data to ensure that the results at hand reflect the true characteristics of the surfaces and not the dynamic properties of the measuring systems. This is particularly true in measurements of the slip-stick phenomena^(20,22,23,25,27,50,69,116) which has been attributed to instantaneous seizure of the surfaces at points of high contact pressure followed by sudden flow or rupture of welded points.

In summary, it may be said that increased normal loads between rubbing surfaces is accompanied by greater friction and wear. In the case of metals the relationship tends to be linear in absence of lubrication, in that the area of true contact between elastic solids is proportional to normal load and in no way related to geometric area of contact. In the case of visco-elastic structures of textile complexity the relationship between load and true contact area is not linear and true area of contact may be controlled in fabric design so as to reduce local pressures and therefore local wear.

TENSION

Few observations have been made of the influence of tension applied during frictional or rubbing tests on rigid solids. In the case of textile materials, where the tension involved in mounting the specimen affects its surface properties, one may expect variation in abrasion results for materials tested with different internal stresses. Sample tension plays a significant role in those abrasion instruments which wear the material to rupture.⁽¹⁷¹⁾ The expression

$$\text{wear life} = \frac{\text{original breaking strength} - \text{tension in sample}}{\text{loss in strength per unit abrasion}}$$

applies in such cases and clearly illustrates the importance of sample tensile condition during test.^(45,90,124,154,187) The importance of having a tensionless sample to permit absorption of strain energies with least permanent damage is manifest in results reported for the behavior of cotton and viscose tire cords in cumulative extension tests.⁽¹¹³⁾ In some apparatuses sample tensions impart higher pressures between fabric and abradant surfaces thus amplifying the effect of tension upon abrasion results.^(44,66,75,103,158,176,177,184) In yarn tests where tensions affect abrasive pressures as well as minimum tensile strengths of the worn material the hyperbolic relationship

$$S_1 = S_2 \sqrt[n]{\frac{g_2}{g_1}},$$

where S is the number of rubs to rupture at a given tension setting, g, and n is a material constant.⁽¹⁷¹⁾ Where other methods of evaluating abrasion damage are used,⁽⁴⁵⁾ such as plotting loss in strength with successive rubs^(43,47) or rubs to a predetermined change in thickness, air permeability, or capacitance,⁽¹⁵²⁾ the tensions applied must be of an order which definitely distorts the fabric structure to have a significant effect on its abrasion resistance. Finally, there are test conditions under which a minimum tension is required to hold the sample firmly against the abradant⁽⁹⁰⁾ and thus prevent early rupture due to snagging as for example in the case of yarn tests where the abradant moves at an angle to the yarn axis.^(73,79,154) However, caution must be exercised to avoid distortion of the sample as a result of such tensions. The answer then as to the effect of sample tension during abrasion, will depend upon the relative magnitude of tension and the character of the wear test.

SPEED OF RUBBING

In considering abrasion as a frictional phenomenon, we find considerable conflicting data reported as to the effect of velocity on the frictional resistance developed between moving surfaces in contact. In many instances μ is reported to be constant over a range of testing velocities.(17,21) In other instances μ between metal surfaces at high pressure was observed to decrease at higher speeds(50) due to a reduction in the extent of welding and plastic flow followed by rupture of fewer welds. This has been demonstrated at lower speeds and lighter pressures as well(34,46) in a range where hydrodynamic lubrication was not present. Where such lubrication is present it has been illustrated that the friction-velocity curve can have a decreasing branch, a minimum, and an increasing part. At low velocities partial metallic contact occurs resulting in considerable stick-slip phenomena, which is reduced as the speed increases and boundary lubrication is activated. At higher speeds the viscosity properties of the film take part in the friction phenomenon and further increases in velocity between surfaces result in large frictional components.(116,156,186) Hydrodynamic lubrication is seen to depend on the shear component, F , of the fluid. In this case

$$F = \eta \frac{du}{dn}$$

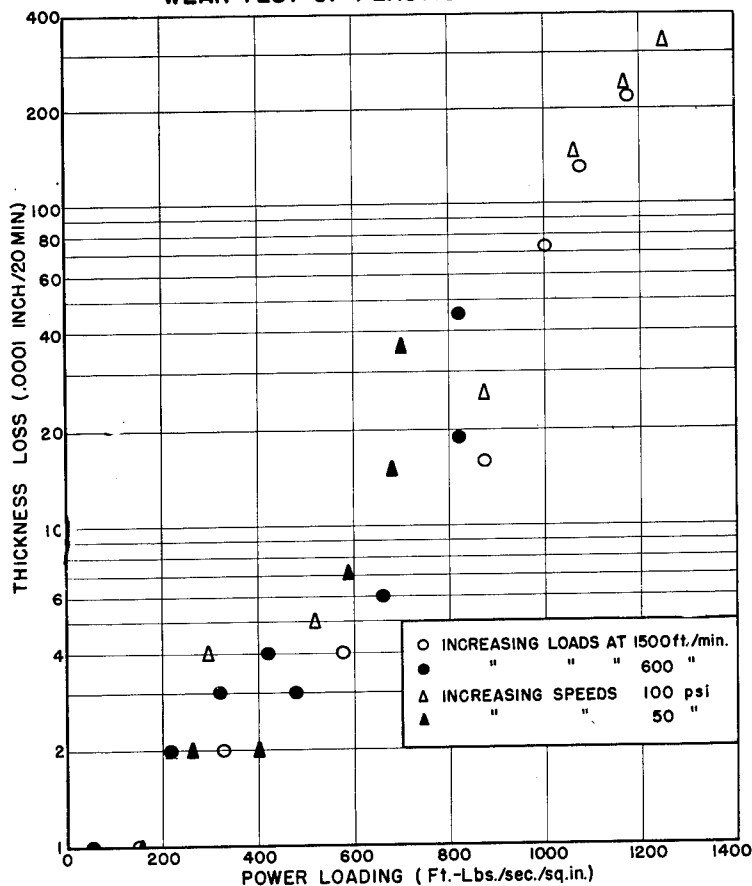
where η is the viscosity, u the velocity of flow at any point, and n the distance from solid surface. If, however, fluid lubrication is not present and speed is increased, it may be expected that temperatures of the rubbing surfaces may increase due to inability of the materials to conduct away the heat.(25,103,116) High temperatures will in turn affect the shear properties of the intermediate films and the solids whose surfaces are in contact,(57,85,186) but this will be discussed later. It is generally concluded that the coefficient of friction of unlubricated metals will generally decrease at higher speeds. Where only boundary lubrication exists higher speeds give higher coefficients due to film destruction.

Since abrasion as a phenomenon introducing stresses below the surface layer(20) due to friction, snagging of surface irregularities, or to snagging of macro segments of the textile yarn or fabric, the inherent properties of the high polymer itself come into play. Numerous studies have reported on the increase in viscosity, shear, and tensile stresses in visco-elastic substances at higher rates of strain.(68,85,101,110,113,115,114,134,170) For example, when expressed mathematically the ratio between the breaking resistance, F , on a textile fiber at any given rate of loading, R , and the breaking resistance, F' , at a standard rate of loading, R' , is

$$\frac{F}{F'} = 1 + 0.1 \log_{10} \frac{R}{R'}$$

where R is the quotient of the known rate of loading in grams per minute and the average denier of the sample tested. The phenomenon has been explained on the basis of the relative activity of secondary versus primary bonds.(134) For as the rate of strain is increased fewer secondary bonds can relax and the total stress on the fiber is borne by both secondary bonds forming lateral cohesion between the molecules of the fiber and primary bonds along the length of the molecule and perpendicular to this direction in fibers such as silk and wool. Under these conditions higher rupture stress and increased modulus of elasticity are observed. Under conditions of low rates of strain the secondary bonds have opportunity to relax and thus throw greater stress onto the primary bonds resulting in lower breaking strengths and lower moduli. With increased modulus one may expect greater frictional energy to be expended at higher speeds of rubbing over a given distance of a textile surface with a resulting decrease in abrasion resistance. Shorter abrasion life at higher rubbing speeds has been observed by several workers in visco-elastic materials,(147,199) while other investigators have reported little or no effect with changing speeds.(158)

Fig.1
WEAR TEST OF PLASTIC COMPOUNDS .



In one case less wear was recorded at higher rubbing speeds. Friction studies conducted on visco-elastic materials have shown no increase in μ in one case⁽⁶⁹⁾ (fiber-on-fiber tests at low velocities), while in all others noted, μ increases at higher speeds.^(29,32,45,51,117,148,220) Too high a rate of relative motion should be avoided to prevent irregular, jerky contact between abradant and specimen surfaces.

The effect of varying speeds has been combined by Dickson⁽⁴⁸⁾ with that of frictional resistance between metal and compounded plastic materials and the term power loading has been introduced, where

$$\text{power loading} = \frac{\text{frictional resistance} \times \text{rubbing speed}}{\text{rubbing area}}$$

As shown in Figure 1, a semilogarithmic relationship exists between thickness losses per unit rubbing time and power loading. A similar relationship was observed between weight loss and power loading. It is significant that increments of power loading are controlled by speed of rubbing and/or normal load between rubbing surfaces. The spread of the points in Figure 1 is attributable to both the testing technique and the physical variations known to exist in the successive specimens tested as a result of evaluations of their other properties. Tests on the same material lot would no doubt improve the correlation. This relationship facilitates prediction of wear performance under varying conditions of pressures and speeds, and rubbing surfaces. The investigator points out that curves for different materials often cross when plotted as in Figure 1. It therefore becomes essential that tests of this nature be conducted in the laboratory at power loadings comparable to those incurred in service in order to ensure valid test data.

In summary, it may be said that speed of rubbing has a variable effect upon the frictional energy absorbed and wear damage to surfaces in contact, depending on the presence of lubrication, the dissipation of frictional heats, and the effect of speed and temperature on the mechanical properties of the material. Nonlubricated metals generally absorb less frictional energy at higher speeds of rubbing while the opposite is true in the case of high polymers constituting the textile structure.

SURFACE TEMPERATURE

The importance of temperature in wear tests is repeatedly stressed in studies of surface rubbing.^(41,100,169,175) Both the initial temperature of the surface and the changes in temperature (due to friction) affect the mechanical properties of surface films and of the base material.^(68,85,92) In the case of polymers the change in

stress-strain ratios with increasing temperatures is sigmoidal, while changes in energy absorption, resilience, etc., with increasing temperatures follow a Gaussian curve and reach a definite maximum at a critical temperature. It is therefore to be expected that surface rubbing which depends on these material characteristics will change in character with temperature variation. Friction measurements on yarns running over materials of varying heat conductivities showed a drop in μ if such conductivity was not high enough to dissipate the heat generated at the rubbing surfaces.(32,117) In another experiment, a highly conducting metal was heated by an outside source and a corresponding reduction in μ noted at the higher temperatures. The same effects have been noted in frictional measurements on metals(18) and in studies of the mechanism of sliding on ice and snow where the conductivity of a ski was shown to be a critical factor in achieving good sliding characteristics.(21) Similar results have been noted in fiber friction tests(97,98,107) and on woven brake linings.(185) However, it has been reported that under conditions where relaxation temperatures of rubbing metals are exceeded, higher μ 's may be expected.(57)

Experiments in rubbing metals emphasize the importance of film and material properties at the temperatures generated during rubbing. It is quite possible for surface temperatures at the points of contact to rise considerably due to the high pressure concentrations involved.(25) Such temperatures are not reflected in the over-all temperature of the solids because of the localized nature of the contact. They are transient in nature and fluctuate rapidly during the rubbing action. Formation of the vitreous Beilby(10,11,61) surfaces of polished metals is representative of this phenomenon,(19,164) for here the metal softens and flows over the rough surface, filling in depressions. It noted that polishing agents must have a melting point above the solid being polished, or else true polishing will not take place. Electron diffraction patterns of polished surfaces show an amorphous or microcrystalline pattern attributable to sudden formation of small crystals in the melted metal. On non-metallic substances the pattern indicates the presence of an oriented layer of microcrystals.

The temperatures incurred in rubbing will depend upon the load, speed, coefficient of friction, and thermal conductivity of the masses.(25, 44,116) Even with well-lubricated metal surfaces temperatures up to 600 C. have been noted giving evidence of local breakdown in fluid and even boundary lubrication. Obviously, a good lubricant is one which will not decompose at such temperatures and will rapidly reform(9,10) to minimize the points of true contact, but this will be discussed later.(1) The limit, of course, in rubbing temperature is established when the melting point of one of the surfaces is reached. This is clearly demonstrated in metal sliding experiments where the slider and base metal of varying melting points are tested and entirely different types of damage are incurred.(18,22)

The rapid fluctuations in temperatures at points of contact between rubbing solid surfaces coincide with the occurrence of stick periods during which high points between the surfaces interlock as the tangential frictional force increases to a point where it exceeds the shear strength of the area of the projections and rapid flow occurs. At low speeds this phenomenon is marked, but at higher speeds its effect is lessened. It is seen that the natural frequency of the weighing and recording system of the friction device and the properties of the materials being rubbed will determine the frequency of these stick-slip cycles at a given velocity of rubbing.(1,50,116)

In experiments on triboelectricity (static caused by rubbing nonconductors) it has been shown that surface strain may be recovered completely by heating the surface of the material to a temperature considerably below its melting point. Since rubbing raises the temperature locally this relaxation may proceed simultaneously with additional strain occurring in continued rubbing.(160,161,162,163) Temperature relaxation of surface strain measured by triboelectric means(164) resemble the relaxation behavior of high polymers under increased ambient temperatures.(92)

In summary, it may be said that the temperatures generated by rubbing will depend upon the normal load between the surfaces, the relative speeds between the two bodies and the thermal conductivity and specific heats of the masses involved. Generally higher temperatures will reduce lubricant and film viscosities and therefore lower the frictional resistance of both metals and textiles. Simultaneously higher temperatures result in softening of metals and in their plastic flow. Similarly, the shear resistance of high polymers is significantly affected at higher temperatures. Thus when lubrication is lacking and shear is the major medium of attrition, one may expect higher temperatures to result in greater wear damage.

PRESENCE OF MOISTURE

Moisture becomes a factor in abrasion and friction tests through its effect upon surface properties(162) and, in the case of organic fibrous materials, upon solid properties.(170) Interposition of films between solid surfaces in contact has been shown above to significantly reduce the coefficient of friction between the bodies and thus reduce rubbing damage. And so it may be expected that a film of adsorbed water vapor will act to reduce the frictional coefficient. However, the coefficient under moist conditions has been shown to be greatly increased (35,98,102,117,185) over that observed with a dry air or the normal contaminant film, and in some cases, an adhesive quality has been evidenced by the water layer,(156) and here one would expect increased abrasion damage.

However, in the case of fibers, moisture has an opposite effect on different materials. With higher moisture content native cellulose fibers(115) are stronger, and artificial cellulose or protein fibers weaker. At the same time, initial Young's modulus and torsional rigidity are usually much lower in fibers which have been subjected to high moisture conditions. On the other hand, the swelling of fibers may stiffen the fabric and significantly reduce its abrasion resistance because of its lowered compliance.(149,176) Fibers which do not absorb appreciable water have not shown marked changes in abrasion resistance when wet, while regenerated cellulose fibers are notably deficient in wet abrasion.(212) And again the surface of the abradant may change significantly in the presence of moisture depending, of course, on the amount present. In view of the variable effects of high humidities on the physical properties of textiles, it is not feasible to generalize on the relationship between moisture content and abrasion resistance of fibrous materials. It may be expected that the condition which increases the shear strength of the fiber and decreases its modulus of elasticity will enhance its abrasion resistance.

EVALUATION OF DAMAGE

In comparing materials with a view to selecting that with the maximum abrasion resistance, it is essential to specify the end point or method of evaluating wear damage. It has been shown that the selection of a point of evaluation may often reverse the relative ranking of materials.(43,88) Numerous methods of measuring wear damage have been proposed.(4,169,214) These include: change in strength, temperature,(45) thickness, weight,(90) surface luster, air permeability,(151) color, character, or appearance. The formation of a hole(44,47,77,99,171,176) or complete loss in strength (and rupture of the specimen under the testing stress)(79,103,124,177) has been used to measure wear damage. Others have preferred to plot the change in strength,(28,72,73,75,128,158) thickness,(152) or air permeability. In cases where rubs to complete failure of the specimen is used as a means of evaluating wear resistance variation in the results have to be treated statistically. One investigator strongly urges the use of control-chart techniques in analyzing yarn abrasion data.(201) Depending on the type of test, both normal and skewed distribution of end points in repeated tests of the same material have been noted. In one of the latter cases it was found most effective to express the abrasion as the mean log cycles to rupture(124) and in the other, the median value cycles to break.(182) Numerous investigators simply assume a normal distribution of rubs to failure and report these results as the mean number of strokes or cycles. The general expression for the wear life of the material may be expressed in terms of a given property (K) as

$$\text{Wear life(120,213)} = \frac{\text{original value of K} - \text{end-point value of K}}{\text{rate of loss in K}} .$$

In the case of bursting,^(172,173) tearing, or tensile strength, it is obvious that the end-point value of K should equal the maximum stress which the material will meet in service.⁽⁴³⁾ Many attempts have been made to calculate this critical value based upon practical experience, but it remains to evaluate a minimum functional strength for each type of material based upon its end-use and service requirements. A most recent and promising technique of evaluating wear is that of measuring the change in capacitance between two plates of a condenser as worn and unworn samples are placed in the air gap.⁽¹⁵²⁾ Here the disadvantage met in the strength tests, that of destroying the sample, is eliminated and rapid measurements of the rate of wear damage on textile specimens can be made. Another technique recently described^(5,71) permits measurement of the change in modulus of elasticity of the material as a result of the repeated micro-loadings of the wear test, and gives valuable information as to the cumulative modification of the physical properties of the fabric, exclusive of its geometry.

The relationship between the various measures of wear as the abrasion test progresses is of importance and is dependent upon the structure or geometry of the material being abraded. For example, it has been shown in plastic wear tests that weight, thickness, and capacitance changes are all directly related.⁽¹⁵²⁾ On fabric, however, the relationships are not direct; in fact, accumulation of debris may maintain fairly constant weight in a fabric structure while thickness is reduced. In the case of strength-weight relationships a concave downward strength-loss curve is noted for successive wear cycles, while the weight-loss curve is concave upward.⁽⁴³⁾ This difference may be explained directly from the geometry of the yarn structure as will be indicated below.⁽¹³²⁾ Yarn and fabric geometry will likewise affect air permeability, weight, strength, and capacitance relationships on worn fabrics. It is concluded that the ideal method for evaluating wear damage is that which permits a nondestructive study of the progressive change of a single character of the material in test. This is of course impossible where an evaluation of the single property is arrived at through destruction of the sample as in the case of breaking, tear, or burst strength. The end point selected should correspond to loss of service utility in the field. Pending development of such a method strength testing at increasing cycle stations is preferred as measure of wear although considerable promise exists for the newly developed sound-modulus and capacitance methods.

MATERIAL PROPERTIES AFFECTING FRICTION AND WEAR

SURFACE CHARACTERISTICS

It is noteworthy that considerable emphasis has been given the importance of surface roughness in frictional studies.^(33,57,123,203) One can but marvel at the increased bearing pressures which can now be sustained with a minimum amount of wear over prolonged periods of high-speed motion between metal surfaces. It has been shown that this improvement has been achieved by preparation of surfaces with super finish "devoid of defective, fragmental, and noncrystalline metal, closely approaching a geometrically smoothed and developed plane of unworked crystalline base metal."⁽²⁰²⁾ In a recent summary on the nature of friction it has been pointed out⁽¹²⁾ that surface roughness provides for the presence of hills and valleys on a given surface with a measurable average inclination, d . When a small body of weight, W , is slid across the above surface, force vectors will be required to lift the weight up and over the hills and projections of the surface. Movement will then take place when the component of the horizontal force, F , acting along the slopes, $F \cos \alpha$, equals $W \sin \alpha$. Thus with no acceleration $\tan \alpha$ equals $\frac{F}{W}$ or the coefficient of friction, μ .

As will be shown below in the discussion of lubrication this expression for μ assumes little or no shearing of the projecting hills, that is a condition of complete lubrication. In fact it has been shown in studies of friction and cutting of metals^(57, 108) that

$$\mu = \frac{S}{H} + \tan \theta$$

where μ is the coefficient of friction, S the shear strength of the average interlocking hill or projection, H the mean pressure surface hardness value of the softer of the two metals and θ the average slope angle of the interlocking projections. This general expression holds when θ is appreciable, but when θ is negligibly small⁽⁷⁴⁾

$$\lim_{\theta \rightarrow 0} \mu = \frac{S}{H}$$

which stresses the material properties of the material being rubbed. But more will be said about material properties. In the expression $F/W = \mu$ it follows that for small values of W , μ will be constant, but at higher loads μ will vary in that a greater portion of the frictional energy will be spent in deforming the hills rather than climbing over them.⁽⁸⁰⁾ The latter case is met in the majority of our abrasion tests and its treatment requires consideration of both surface roughness and

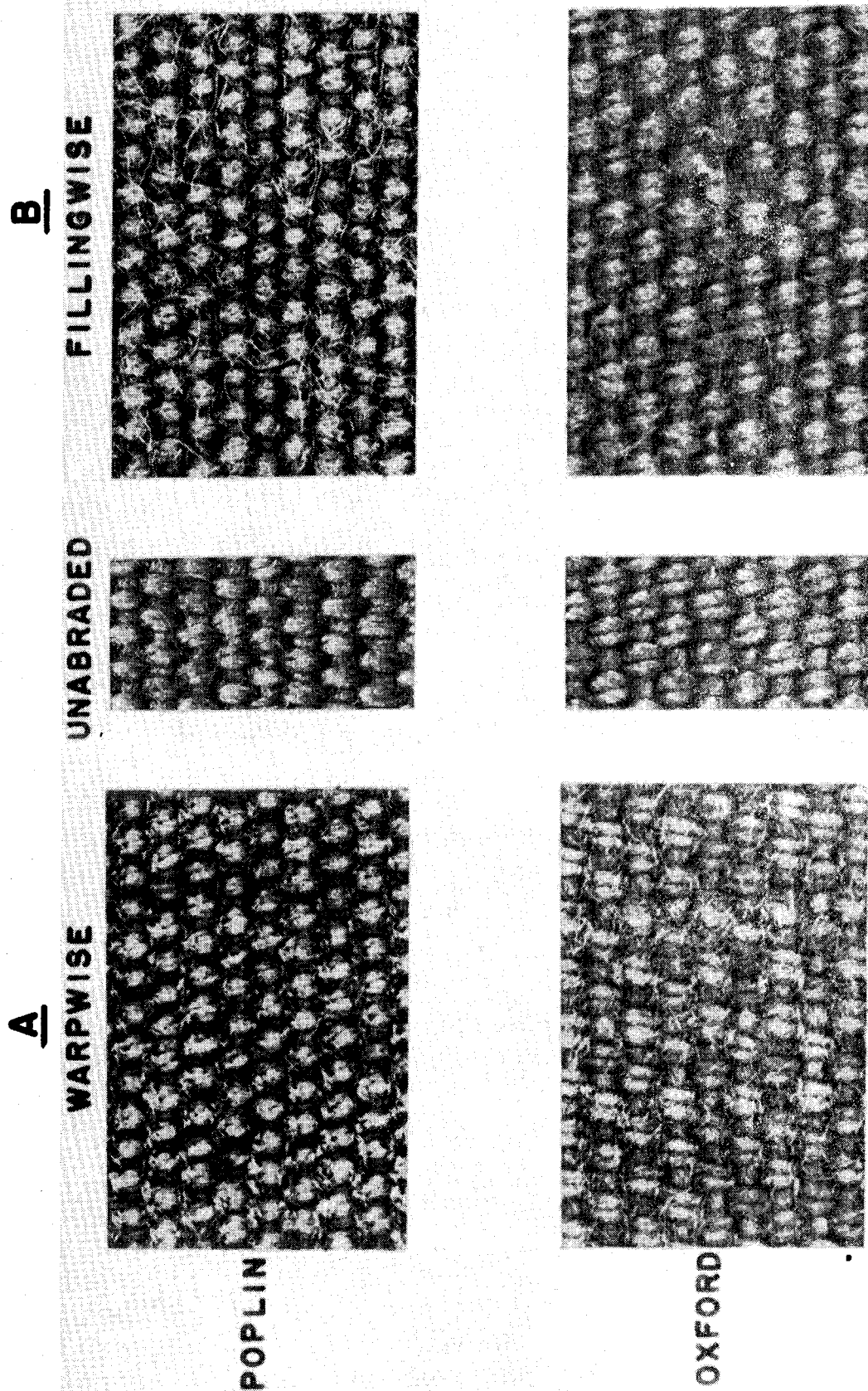
material properties.(147,150,202,203,220) All in all, the concept as presented implies a strong relationship between friction and wear and these two phenomena blend into a spectrum of simultaneous mechanisms which are ever present in all movements between surfaces in contact. By the same token, one may include in these studies such hitherto subjective evaluations as surface softness, harshness,(117) smoothness, and waxiness, and even the screech of brakes caused by surface elements(148) in mechanical relaxation oscillation.(13)

As contrasted to solid materials, textile fabrics undergo a twofold breakdown in rubbing, one consisting of loss in internal cohesion of the fiber structure, such as is met in surface attrition, transverse shear, flexural fatigue and tensile stress, and the second involving direct breakdown of yarn structure through fiber snagging and subsequent untwisting.(118) The relative importance of each mechanism is dependent upon the nature of the abradant and, as will be shown later, the structure of the fabric.

Internal fiber cohesion may be overcome through gradual attrition or through sudden partial disintegration or total rupture. Smooth abradants wear away the fiber surface in a gradual manner which may be studied by the special staining techniques of optical microscopy(30,39) or with the replica metallic shadow-casting methods of electron microscopy.(81,82,121,157,179,208) Sharp abrasion on the other hand will cause the more sudden rupture of individual fibers,(171) quite unlike the surface attrition met in restricted service wear but nevertheless common to rough usage of utility garments. On this account a great deal has been said about the inadequacies of emery abradants which completely shear the surface fibers.(128,171) This has been observed at the Quartermaster laboratories when emery abrasion takes place in the warpwise direction of tight, sharp-knuckled poplins and oxfords(3) (Figure 2A). The tendency of emery abrasives to shear the surface fibers is somewhat reduced in the case of herringbone twills, sateens and denims, in which the fibers have an opportunity to move within the yarn structure and thus reduce the points of excess local strain.

Fiber snagging and subsequent untwisting of the yarn are more common when extremely rough surfaces come in contact with the fabric. This is typical of the wear which occurs when fabrics are used in combat, fatigue duty, farming, or sports.(212) Intermediate launderings, of course, assist in removing short sections of fibers which have been ruptured during the snagging action. Nevertheless it follows that the percentage of shorter fibers in a fabric will increase during rough service.(67) It has been observed that this same type of breakdown takes place when emery abrasion is directed perpendicularly

Fig. 2
EFFECT OF DIRECTION OF ABRASION ON COTTON FABRICS
 (Mag. 10x)



to the axis of the yarn crowns, even on tightly woven fabrics (See Figure 2B). Since both fiber rupture and snagging occur in emery rubbing tests, it would appear quite logical to retain emery or other sharp particle surfaces as an abradant in testing utility fabrics, and this course has been adopted by the Quartermaster laboratories. It is nevertheless recognized that emery surfaces suffer significant changes during rubbing⁽⁴⁵⁾ and so their use must be confined to comparative tests. Other investigators have used a variety of rubbing surfaces both smooth and rough to evaluate the abrasion resistance of fabrics, and upon finding similar rankings for a number of fabrics with widely varying surfaces have standardized on the use of carborundum^(43,95,103,166,167) or emery paper.^(158,171,184) Still others adhere to the use of fabric abradants to achieve the gradual attrition evidenced in microscopic examinations of restricted service-worn clothing.^(28,47,90,91,128) Finally, there are those who utilize such items as card clothing to achieve the "teasing-out" effect so often noted in field wear, while others prefer metal screens,^(75,204) files, blades,^(55,152) or bars.⁽¹²⁴⁾

The important factor from a practical point of view is the choice of an abradant which will rank textile materials as to abrasion resistance in the same order as the abrasive surfaces which they will meet in service.^(45,171,200) Such a requirement is, of course, complicated by the fact that rubbing surfaces in actual service may differ significantly.^(49,59,145,154,175) In working with military garments one must consider the activities of a clerk seated at a desk the major portion of the day against a man who spends his time in vigorous fatigue or combat duty. Uniforms provided for varying activities are usually made of different materials, but frequently similar materials are exposed to widely diverse abrading surfaces. Quartermaster test data in these instances show that changing the natural type of the rubbing surface does not often reverse the abrasion ranking of materials, but does demonstrate fluctuating degrees of difference among the materials. An excellent example of this is presented in the data of a Quartermaster test of wool, nylon, and wool-nylon glove inserts.⁽¹⁴³⁾ In this test the glove inserts were worn by men engaged in manual labor; in one case leather shells were worn over the inserts, and in the other the inserts were worn alone. Data shown in Table I demonstrate the significant superiority of the nylon-wool and the nylon inserts over the all-wool inserts in the harsh abrasion to which the items were subjected when worn alone. With the same type of action, but restricting the abrasive surface to the inside of the leather shell, little or no difference was noted between certain of the all-wool inserts and the nylon blends.

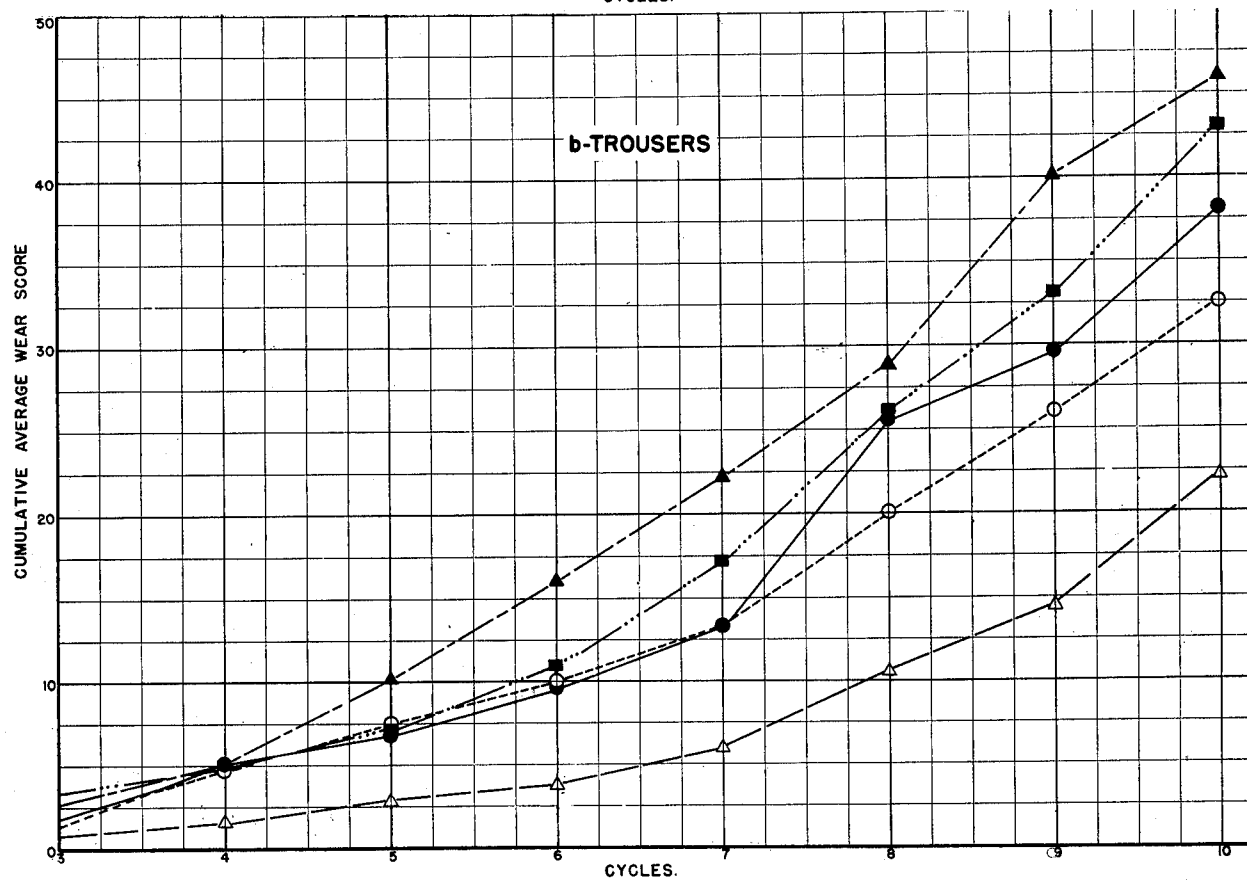
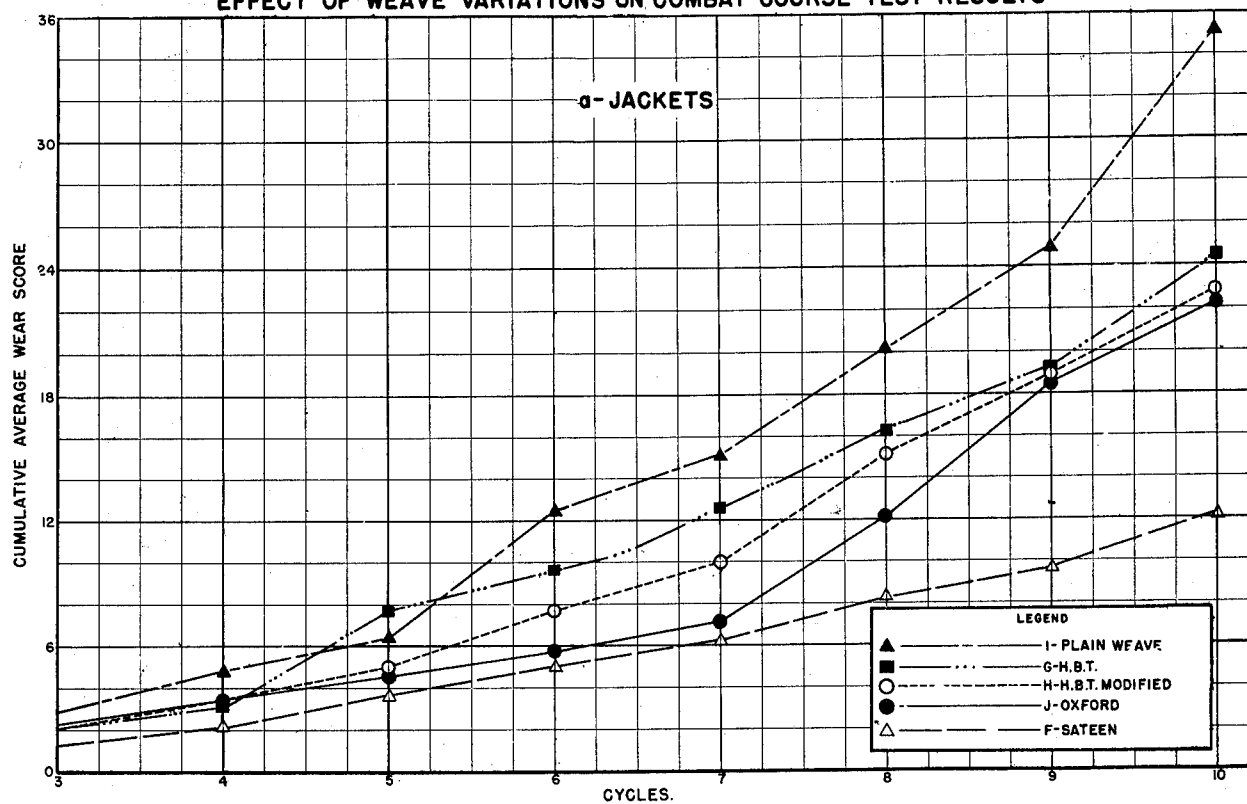
Other examples of this phenomenon are seen in service tests^(3,8,89) of textile garments, where the abrasion differences among materials will differ depending upon the part of the garment in which it is worn.⁽⁶⁷⁾ The data of Figure 3 illustrate significant differences in wear scores for fabrics which vary in weave structure. The fabrics had been made up into

TABLE I

Test of Gloves Insert with Varying Percentages
of Wool and Nylon⁽¹⁴³⁾

Lot	Type	Without Shell		With Shell	
		Avg. No. of Travers.	Rank	Avg. No. of Travers.	Rank
I	75 wool 25 nylon	27.4	3	83.7	7
II	100 wool fulled, unbrushed	17.6	7	71.0	9
III	100 wool, shrink resistant, fulled, unbrushed 56's	9.0	9	71.5	8
IV	100 wool, medium brushed, no shrink resistance	10.6	8	102.2	4
V	65 wool 56's, 35 nylon, 6 denier fulled, medium brushed, shrink res.	20.3	6	83.8	6
VI	35 wool 56's, 35 nylon, 6 denier fulled, medium brushed, untreated	25.7	4	85.4	5
VII	35 wool 56's, 65 nylon, 6 denier fulled, medium brushed, shrink res.	43.6	2	105.6	3
VIII	100 nylon, 6 denier fulled, medium brushed, shrink res.	56.6	1	108.4	1
IX	100 wool 56's fulled, medium brushed, shrink res.	22.0	5	107.0	2

Fig.3
EFFECT OF WEAVE VARIATIONS ON COMBAT-COURSE TEST RESULTS



jackets and trousers and given several traversals over the combat course at the Quartermaster Board, Camp Lee, Va. While the plain weave and sateen weaves retain their respective rankings as poorest and best in wear resistance, respectively, the modified herringbone-twill and oxford fabrics are seen to reverse in wear scores, although the differences are not statistically significant. Reversals in the abrasion resistance of cotton and wool fabrics have been observed when grey, then mineral-dyed duck, was used as the rubbing surface.⁽⁴⁷⁾ These same differences existed even after the waxes which might have served to invalidate the results, were carefully removed from the fabrics. Similarly, cotton and spun-viscose fabrics are rated in reverse order of abrasion resistance when tested against card clothing, then against wool.⁽⁹⁵⁾ Such reversals are attributable only to differences in abrasives as they affect the test specimen^(79,175) and are not at all surprising in view of similar inconsistencies in measuring the coefficient of friction of several different solids against each other. Generally speaking, anomalous data in comparing field and laboratory tests may be expected as a result of differences in contact surfaces. It should be pointed out, however, that such reversals do not come about solely as a result of variations in coefficients of friction, but that other surface properties are involved.

In summary, it may be said that the surface of the abradant is responsible to a major degree for the character of fabric attrition. However, fabric structure and direction of abrasion are ever-present interacting agents which must be considered in comparing the abrasive effects of various rubbing surfaces. It remains to study the characteristics of the contact surfaces encountered in actual wear and to attempt their simulation in the laboratory.

LUBRICATION

It has been said that we are fortunate that clean surfaces do not exist in practice. The speed of our present-day transit and the wear life of all solid bodies subjected to motion would be seriously impaired were it not for the formation of surface films, intentional or otherwise, which serve as lubricants between rubbing surfaces. Without such films, as has been shown in experiments with degassed solid surfaces, significant increase in the frictional coefficient^(1,18) may be expected. The mere re-entry of gases to the experimental chamber creates an instantaneous film on the metals studied with a resultant drop in μ .⁽²⁰⁾ As such films continue to form with time μ falls off at a decreasing rate. Whether viewed from the standpoint of reduction in adhesion forces or reduction in shear strength, the presence of this monomolecular layer of adsorbed gas or contaminant radically changes the friction and wear relationships between solid bodies in motion.⁽³⁵⁾

Amontons' law is generally found to apply in the presence of surface films between 10^{-8} to $5 \cdot 10^{-4}$ cm. thick,⁽¹⁵⁶⁾ wherein solid-to-film shear resistance is a significant element.⁽⁴¹⁾ This condition has been termed boundary friction,^(13,86,10) and is often met in wear and abrasion tests of fabrics and clothing. Extension of the film thickness beyond 0.1×10^{-4} cm. from the solid surface introduces the viscosity function of the film or fluid⁽⁷⁾ in question (or shear in the case of solid lubricants such as graphite), and is termed a condition of complete (hydrodynamic) lubrication. Considerable research has been conducted to establish the extent of deep surface orientation of liquids⁽⁷⁸⁾ which will affect their performance as fluid lubricants. It has been pointed out⁽⁵⁷⁾ that the condition of perfect boundary lubrication calling for an adsorbed film which permits no metal-to-metal contact but which possesses negligible shear strength is a limiting case of the expression cited above, that is

$$\lim_{S \rightarrow 0} \mu = \tan \theta$$

Here surface roughness and contact angles are the sole factors in determining frictional energies.⁽⁷⁴⁾

The wear damage occurring at surfaces which are rubbed in the presence of complete lubricants gives evidence of breakdown in hydrodynamic and even boundary lubrication⁽⁸⁶⁾ at isolated points of high contact pressure. The adequacy of a complete lubricant can be described in terms of the amount of such breakdown which occurs during rubbing and the ease with which the unlubricated portions are quickly protected against further damage by spreading of the lubricant. The desirable complete lubricant⁽¹⁾ is one which (1) has a sufficiently high viscosity to drag the fluid between the moving parts and thus prevent true contact between surfaces; (2) has enough viscosity to prevent its being squeezed out from between contact points of high pressure, (3) not too high a viscosity lest fluid friction be increased; (4) has a safety level or reserve designed to offset the amount of lubricant decomposed at the high temperatures incurred at local points of rubbing and to balance the presence of contaminants. It has been found that the best over-all lubrication is achieved with fluids possessing low contact angles. In the case of boundary lubricants, a definite relationship has been shown^(10,74) between the chemical structure of the film material and the coefficient of friction between film-covered surfaces.

The occurrence of the two types of lubrication will vary with speed and is reflected in the nature of the stick-slip phenomenon and in the friction-velocity curve^(34,116,186) for well-lubricated surfaces. At very low speeds partial lubrication and partial solid contact takes place and high coefficients result. As speeds increase less solid

contact occurs and boundary lubrication predominates with a resultant lowering of μ . Fluid lubrication becomes of greater importance with still higher speeds and the subsequent increase in μ reflects the increased viscous resistance of the fluid to high-speed shear. There is also evidence to the effect that higher speeds of rubbing will convert nonpolar lubricating films to polar films, achieving a more closely packed monomolecular layer which gives evidence of additional viscous effects due to increased orientation of the film molecules. (34, 35, 191)

The use of lubricants has often been proposed as a means of extending the wear life of textiles. It has been the experience of the Quartermaster laboratories that small percentages of lubricants may be beneficial to the abrasion life of cotton fabric as measured, but this is not always borne out in service. In one of three field tests in which the Quartermaster Corps participated, improvement of the treated fabric was noted due in part to the reduced laundering resulting from the stain-resisting character of the lubricant. In the other tests where uniform laundering procedure was followed little difference existed between treated and untreated materials after extended periods of use. Lubricants have been found extremely useful in reducing the amount of thread damage occurring during the sewing operation. It has in fact, been possible to sew with a high degree of seam efficiency, fabrics which in the unlubricated state were perforated in the manufacture of shirts and were torn as easily as paper. Textile lubricants are generally looked upon as enhancing fiber and yarn movement within the fabric and will contribute in varying degrees to increased sewability, more seam slippage, higher laboratory abrasion resistance, and on occasions, improved wear life.

It is concluded that conduct of abrasion tests without control of lubrication is misleading. In the use of metals every attempt is made to maintain hydrodynamic lubrication as a means of reducing wear. However, under the most ideal conditions boundary lubrication will prevail at local points and often true contact with its high abrasive damage will occur. Boundary lubrication is the common condition of textile use with some breakthrough resulting in surface attrition and it is here that physical properties of both the lubricant and the solid, together with surface roughness determine the extent of rubbing damage.

MECHANICAL PROPERTIES

The nature of friction is indeed complex and its effects extend to a considerable depth below the surface of the solid. (20, 22, 41, 50, 78, 102) It follows that the mechanical properties of the material play an important part in determining the frictional (35, 186) and wear properties of solid bodies. (46, 147, 191) The formation of welds or bridges at points of true contact and their subsequent rupture, or the ploughing of one material through the surface projections of another is dependent upon the tensile, compressional, and shear performance of the material at the temperatures developed during rubbing. (1, 24) The occurrence of the stick-slip phenomenon in which the area of true contact between

surfaces builds up then suddenly falls off has been conclusively shown to be dependent upon the mechanical properties of the rubbing bodies as well as the recording system in the friction test.⁽¹¹⁶⁾ Similarly the formation of chips and the transverse flow of metals during machining have been shown to depend upon the mechanical properties of the base solid as well as upon its friction against the cutting edge and the rake angle of the cutting tool.^(56, 57, 58)

Depending on the materials present and the conditions of lubrication, various degrees of welding (involving melting temperatures) or ploughing (which may take place at temperatures below the melting point of either solid⁽¹¹⁶⁾) may be expected, and these will be reflected in the occurrence of flash temperatures and in contact-area changes at the moment of slip or during the stick period.^(1, 22) Where a small surface (of a slider) possesses greater hardness at high temperatures than the base material of greater area, the area of contact drops suddenly at the slip point and builds up during the stick period, indicating a ploughing action to be taking place. Under these conditions it has been shown that the amount of damage is proportional to the relative softness of the base material.^(149, 150) If the slider has a lower melting point than the base material, welding occurs due to melting of the slider surface and the area of contact builds up to a maximum just after the slip, due, it has been shown, to plastic flow; as the pull continues, rupture of the welds occurs, leaving traces of the low-melting slider material on the high-melting base. Where equivalent surfaces are rubbed equal welding and flow occurs and both surfaces are distorted and torn. Here, greatest abrasive damage is experienced,⁽²²⁾ and the occurrence of the stick-slip phenomena is less regular. In experiments of this type, it has been demonstrated that the frictional forces effective between solids are of the same order of magnitude as the product of the areas of ploughed projections and/or weld ruptures observed at the surfaces and the shear strength of the material.⁽⁵⁰⁾

The surface temperature between rubbed solids depends upon the speed of sliding and the normal forces between the surfaces. The temperature is limited, however, by the melting point of the lowest-melting solid. It has been observed that very high flash temperatures occur even in well-lubricated systems.⁽²⁵⁾ Such local concentration of high temperature is due to dissipation of mechanical energy stored at the surface of the solid and depends on the speed of movement and the conductivities of the solids.

Damage incurred in the case of elastic deformation of metals has been shown to be proportional to the load and independent of geometric area, thus following the classical laws of friction.⁽¹⁵⁰⁾ It is noteworthy that for plastic deformation the damage to sliding bodies is proportional to the geometric area of contact.⁽¹⁴⁹⁾ This will be discussed later at greater length.

The importance of material properties in determining the wear resistance of textile fabrics has been cited many times, but only recently has any attempt been made to relate the tensile behavior of textile fibers with their abrasion behavior. The use of breaking strength as one of the major criteria of manufacturing control has led the consuming public to judge wear resistance in terms of tenacity. But this impression is quickly corrected when one judges the relative abrasion resistance of uncoated glass or saponified acetate, both of which possess extremely high tenacity but lack in ability to elongate under load. The importance of elongation has been recognized as a requisite to abrasion resistance.^(147, 168, 171) Defined more critically, the desirable stress-strain properties of a fiber have been listed as follows:^(70, 72)

- (a) a low modulus of elasticity
- (b) a large immediate elastic deflection
- (c) a high ratio of primary to secondary creep
- (d) a high magnitude of primary creep
- (e) a high rate of primary creep

The difference between these elements, which appear to favor surface softness, and the hardness thought to be desirable for minimum damage to a metal surface lies in the inherent assumption in severe textile wear that the abrading surface will possess a much higher order of hardness than the fiber (except perhaps in the case of glass fibers). It therefore becomes desirable for the polymeric surface to "give" completely with each passage of an abradant particle to prevent the setting up of critical tensile or shear stresses at concentrated points. Behavior of the surface upon approach of the second and subsequent abradant particles will depend of course upon the recovery of the material to its original position and on its continued ability to give. On the other hand, where normal service brings the textile in contact with materials of an equivalent order of hardness, this property assumes greater significance. Here one observes the possibility of reversal of abrasion performance from field to laboratory depending upon the relative hardness of the rubbing surfaces.

In view of the different speeds with which various fibers will recover from small strains as evidenced by the difference in liveliness of wool, cotton, rayon, or nylon fabrics, it is to be expected that the relative recovery of the individual fiber between successive blows by particle projections of an abradant will depend to some degree upon impact frequency as determined by the spacing of the particles and the speed of rubbing. Herein we see a possible cause for reversal of abrasion results on a given set of fibers (in fabric form) depending on the nature of the abradant and the speed of rub.⁽¹⁷⁵⁾ An example of this mechanism is manifest in the reports of cumulative extension tests⁽¹¹³⁾ on cotton and viscose tire cords referred to above. In this case increased speeds of extension reduced

the amount of viscous flow and permitted elastic recovery to contribute to the cycle life of the cord, although actual test time was decreased. Such information points to the need for the measurement of the properties cited above at the frequencies and the degree of strain to be met in actual wear.

Discounting the occurrence of isolated reversals in the ranks of wear resistance of the various textile fibers, one may conclude from published data that the following order from highest to lowest abrasion resistance applies to the most common textile fibers: (79, 147, 154, 167)

Nylon
Cotton
Wool*
Viscose Rayon (medium high tenacity)
Cuprammonium rayon
Viscose rayon (normal tenacity)
Acetate Rayon**
Casein

With regard to one source of the data reported above (154) it is of interest to note that the ranking was based both upon actual wear tests of men's socks and upon a laboratory index which combined breaking strength and flexing and abrasion performance in both wet and dry states of the fiber. In another case, eight properties were combined in a single index: (15) tensile strength wet and dry, elasticity, knot strength, elongation, tensile fatigue resistance, flexural endurance, and degree of polymerization. It is of utmost importance to designate the finish of the fiber being tested, for this factor often holds the key to modified mechanical properties or surface lubrication. (140, 171, 178, 200, 218)

During the war the Quartermaster Corps evaluated the relative wear resistance of numerous fabric constructions, fiber variables, and blends. Army interest in the wearing qualities of available commercial fibers, both alone and in blends with other fibers, is directed towards:

- (a) development of fabrics of improved wear resistance commensurate with other requirements of weight, warmth, and flexibility.
- (b) reinforcing the wearing qualities of other fibers whose use may be dictated by economics or desirable physical requirements.
- (c) permitting ready substitution of new fibers for currently used materials in the event of material or production equipment shortages, without seriously detracting from wear resistance of the resultant fabric.

* Also reported as superior to cotton

** Also reported superior to normal tenacity viscose rayon. (72, 168)

While numerous laboratory tests were run to evaluate the performance of the various fibers, no attempt will be made here to report all such data. However, wherever the results of field tests are available they will be included since they are the only criteria which may be deemed completely acceptable as of this date and upon which current procurements for the Army may be based. In order to bridge this gap several Quartermaster studies have been conducted to relate laboratory and field indices of wear.(88, 177)

As the first case we consider the relative durability of cotton fabrics and cotton-nylon blends in a fatigue uniform as evaluated on the combat course. The construction data for the fabrics involved and the wear scores reported from the Quartermaster Board are cited in Table II.(138, 217)

TABLE II

Combat-Course Tests of Cotton-Nylon Herringbone Twill Fabrics

<u>Fiber Content</u> (% Cotton)		<u>Fabrics</u>				<u>Average Wear Score at Each Cycle Stage</u>							
		<u>Construction</u>				<u>Trousers</u>				<u>Jackets</u>			
		<u>Yarn No.</u>		<u>Texture</u>		<u>6</u>		<u>12</u>		<u>18</u>		<u>24</u>	
w	f	w	f	w	f	6	12	18	24	6	12	18	24
100 x 100		13	10	84	63	1.5	5.2	8.3	15.1	1.6	6.4	10.5	13.3
100 x 75		13	10	85	65	1.0	3.2	4.9	8.8	4.2	8.3	12.4	17.6
100 x 50		13	10	84	65	1.4	4.0	5.0	9.0	1.9	7.0	10.3	14.1

The object of this test was to evaluate the utility of including minor percentages of nylon in the filling yarn (12.5 and 25 per cent on weight of fabric) of sateen fabrics as a means of reinforcing those structural members of the cloth which are subjected to the major abrasive stresses. The data show a significant improvement in the wear life of the cotton trouser for the nylon-cotton blends, although there is no significant difference demonstrated between blends of 25 and 50 per cent nylon in the filling. It was thought that the difference between the two nylon blends might have been vitiated by early breakdown of the all-cotton warp, but it was observed in the field test that the filling failed first in 96 per cent of the cases for all three fabrics. A further anomaly is evident in the jacket data where the 25 per cent nylon blend is shown to be slightly poorer than the 50 per cent nylon and all-cotton garments. The significant fact to be derived from these tests is that nylon blends can be used to extend the wear life of fatigue trousers with fairly low percentage of the synthetic polymer based upon the weight of the cotton fabric. Further experimentation is warranted, however, to fix the optimum blends for maximum durability depending upon the type of wear to which the garment will be subjected.

The importance of the conditions of abrasion and use of the fabric are again displayed in evaluations of the wear resistance of glove inserts made of wool and wool-nylon blends (Table I, page 26). Here it is seen that the nylon serves as a significant reinforcement for the wool when the glove is subjected to the coarse abrasive action of the Camp Lee glove course; but when the abradant is radically altered, although all other conditions remain the same, certain of the all-wool materials stand up with the nylon blends.

Still another type of wear was studied in the case of flags. It was noted here that all-wool flags disintegrated within 24 hours of severe flexing in a strong wind, whereas blends of 75 per cent nylon and 25 per cent wool stood five to ten times the exposure of the wool item before failure occurred.

As for blends of wool, cotton, and rayon, considerable research was conducted at the beginning of the war. Here the object was to evaluate the effect of blends of cotton, viscose rayon, and acetate rayon upon the wearing properties of 18-ounce serge, the worsted fabric purchased in greatest quantity during the emergency. The possibility of a wool shortage at that time was real and every preparation was made for relieving the critical wool shortage with one of several constructions. As it happened, the need to convert was overcome and the results of the field tests reported in Table III were held in readiness for further emergency changes in specification requirements. Summarized, the results point to the superior durability of the cotton-wool blend over the all-wool product; however, the loss in other desirable characteristics, such as hand, drape, crease retention, and crease resistance, served as the deterrent to immediate adoption of experimental fabric No. 4. The rayon blends, on the other hand, (both viscose and acetate) were shown to significantly affect the wear life of the fabrics, depending upon the percentage of the blend. It was indicated that 15 per cent rayon could be included in the fabric without seriously reducing its wear life or affecting its crease properties. However, it was deemed inadvisable to include more than 15 per cent rayon from the standpoint of fabric warmth and appearance.

It is concluded that hardness of metals at the temperature developed during rubbing is a major factor in determining wear damage. In the wearing of textiles, however, the abrasive surface is invariably harder than the fiber and so those fiber properties which permit translational movement of the point of contact with resultant reduction in the stress concentration, will enhance wear resistance. When combined with high shear strength an optimum balance may be reached for each type of wear met in service. Field tests of various blends as a part of the Army development program confirm these points. The interaction of shear strength and tensile modulus will be discussed in greater detail in part D2 of this paper.

TABLE III

Wear Tests of 15 Serge Fabrics

Fabric	Wt/yd 56" wide (ounces)	Yarn	Texture w f	Fiber Comp. (per cent)	Spinning System	Wear Score*
1	16	2/28	70 50	100 wool	worsted	101 ± 11**
2	16	2/32	76 64	100 wool	worsted	141 ± 30
3	20	2/22	68 54	100 wool	worsted	158 ± 19
4	18	2/25	68 54	70 wool 30 cotton	merino French worsted	89 ± 11
5	18	2/24	68 54	85 wool 15 viscose	worsted	157 ± 26
6	18	2/24	68 54	70 wool 30 viscose	worsted	151 ± 14
7	18	2/28	72 60	70 wool 30 viscose	worsted	169 ± 12
8	18	2/24	68 54	55 wool 45 viscose	worsted	188 ± 19
9	18	2/24	68 54	40 wool 60 viscose	worsted	171 ± 20
10	18	2/24	68 54	40 wool 60 viscose	cotton	224 ± 20
11	18	2/24	68 54	85 wool 15 acetate	--	153 ± 15
12	18	2/24	68 54	70 wool 30 acetate	--	219 ± 20
13	18	2/24	68 54	100 wool (standard)	worsted	139 ± 14
14	18	2/24	68 54	85 wool 15 acetate	--	149 ± 21
15	18	2/24	68 54	70 wool 30 acetate	--	183 ± 24

* Based on combat course wear scores on 8 trousers of each fabric type. (The higher the wear score, the less durable the garment.)

** Standard error of the average wear score calculated by H. F. Schiefer(153) using the formula $\sigma_A = \frac{\sqrt{\sum d^2}}{\sqrt{n(n-1)}}$ where n is the number of traversals of each fabric (i.e., 8) and d is the deviation from the mean.

CHANGE IN SURFACE AND MATERIAL PROPERTIES DURING WEAR

The change in surface properties of a given solid material as a result of rubbing will depend upon the severity of the action, that is, the nature of the rubbing or abrading surface, the normal pressure and relative speed, the interposing films, and the temperature generated during rubbing.⁽²⁰²⁾ In studies of triboelectricity⁽¹⁶⁴⁾ it has been shown that a significant drop in the coefficient of friction between glass rods occurs with successive rubs of one of the rods with a textile fabric. Even when special precautions are taken to thoroughly clean the fabric, and thus remove all oils and waxes, the coefficient of friction of the glass rods so rubbed still drops off, although a bit more slowly. It has been shown that static charges which can be generated by stroking the previously rubbed glass vary in a manner related to the coefficient of friction. This phenomenon has been attributed to the surface strain of the glass (as a result of repeated rubs) and to formation of organic films on its surface. The conclusion is borne out by subsequent treatments designed to dissipate the organic film, and to relax the surface strain by: (1) heating the glass at 220 C. in air which quickly increased μ ; (2) placing the glass in vacuum which also quickly increased μ ; and (3) leaving the glass in air under which condition μ increased very slowly. These experiments were carried further and glass surfaces whose μ had been reduced by successive rubs were treated with chromic acid to remove all traces of surface film. Here the coefficient acted as indicated above, giving evidence to the fact that surface strain caused the major factor in altering μ . These experiments were extended to show that surface condition is dependent upon the presence of acid, alkaline, or aqueous films; the effect of temperature changes due to rubbing; the surface strains produced in rubbing; and the continuous rupture which proceeds as the solids slide over one another.

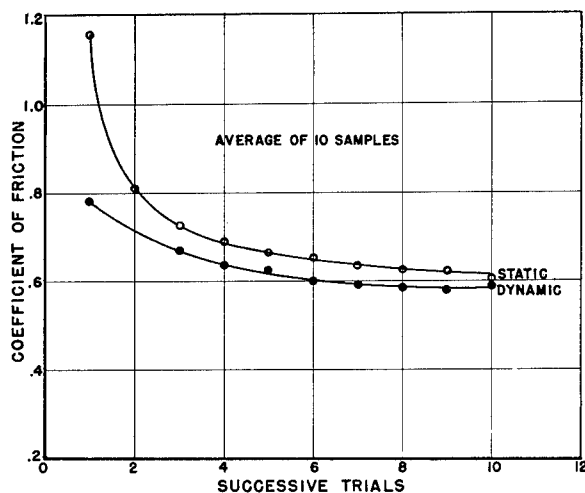
Further work in this field^(160, 163) has shown that intermediate ranges of heat incurred during rubbing introduce greater effects at the rubbing surfaces.⁽⁵⁷⁾ However, when surface temperatures reach a definite percentage of the melting temperature of the solid, a balance is reached between strain recovery and continued rubbing strains. It is noteworthy that this phenomenon is noted below the temperature necessary to melt the solid or achieve the degree of plastic flow or shear described above. These experiments conducted originally on elastic solids were repeated on celluloid surfaces and similar results were reported. When the experiments were run in vacuum, like trends were observed leading to the conclusion that air films were not responsible for the surface changes but that strain was the major factor. Finally, it was shown that less surface change took place on the harder of the two surfaces rubbed.^(160, 161)

Later work^(9, 18, 35) has confirmed the lowering of μ with subsequent rubbing, but here it was thought that creation of oxide films caused the drop in μ . When repeated in vacuum the experiments again showed a loss in μ attributed in this case to release of contaminants

to serve as boundary lubricants. On the other hand, it has been shown that successive rubs between surfaces which have been lubricated cause an increase in μ due to loss in lubrication. The extent of this increase is found to be inversely related to the thickness of the lubricating film and to its self-repairing ability.

In the case of high-speed rubbing under heavy loads, it has been noted that considerable transfer of the softer material can take place, leading to a coating of the second surface.^(25, 46, 149, 152) Conditions of this type automatically produce a modification of the frictional coefficient, for the surfaces in contact are now the same and the high damage consequence of rubbing like surfaces is noted. In some instances such transfer will serve to reduce the coefficient of friction and the resulting abrasion.⁽¹⁸⁾ The entire procedure in grinding and polishing involves modification of the surface roughness by introducing plastic flow at projecting points of the surface into the adjacent valleys with a resulting smoothing of the surface.^(19, 61) The character of this surface has been shown to differ from the properties of the underlying material, and it has long been termed the Beilby layer.^{(11, 159, 202)*} A deliberate attempt to modify the surface structure to improve its load-carrying capacity has been made⁽¹⁹¹⁾ using lubricants which combine, under the effect of heat caused by high speeds and pressure, with the surface to form new and more durable compounds.

Fig. 4
VARIATION OF FRICTION WITH NUMBER OF RUBS
(HERRINGBONE TWILL AGAINST HERRINGBONE TWILL)



* Recently it has been found possible to include preferential (temperature) polishing agents (as tricresyl phosphate) in oil lubricants to achieve a rapid polishing of the surfaces and a subsequent low rate of wear.⁽¹⁰⁾

Surface changes due to rubbing are, as expected, much greater in the case of textile materials. It is difficult to obtain a friction reading at low pressures on a textile fabric without significantly altering the surface of the fibers.⁽¹¹⁷⁾ Subsequent measurements of μ give lower values and only after several rubs will μ reach a point of relative equilibrium.^(51, 109) This behavior has been confirmed in Quartermaster experiments,⁽⁵³⁾ the results of which are plotted in Figure 4. Here it is evident that some orientation of the textile surface takes place during the first few rubs; the surface then appears to approach a state of equilibrium as reflected by the end values of .58 and .61 for dynamic and static coefficients, respectively. Finally it is important to account for the significant changes which occur to the material properties of the textile fiber during normal wear.^(106, 171) One cannot add the effects of laundering, photochemical degradation or mechanical fatigue to the results of pure abrasion for the interrelationships involved are indeed complex.^(67, 178) A study of the Russian treatment of these interactions is warranted.⁽⁶⁰⁾ It remains to conduct abrasion tests on fabrics which have in some way been exposed to the conditions to be met in service.^(4, 45, 59, 133, 145, 186)

In considering the mechanics of abrasion changes in both abradant and specimen surfaces are to be expected. The study of the uniformity and constancy of abradants has been reported many times. Thus far most investigators have concluded that abradant surfaces will vary during the course of the test^(33, 46, 100, 177) and will vary initially from abradant to abradant, thus necessitating the calibration of each new abradant prior to the testing of experimental samples.^(43, 79) This has been the practice followed at the Quartermaster laboratories.

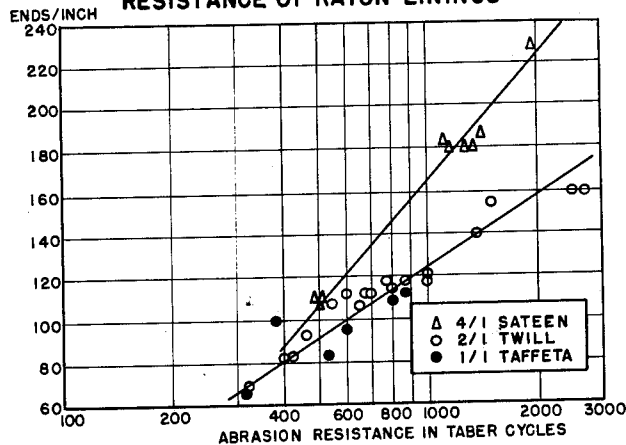
During the course of most abrasion tests the abradant usually becomes dull and the wear rate falls off as the surfaces "wear in,"^(33, 86, 177) unless special provisions are made to renew the surface of the abradant coming in contact with the sample. This has been done by rotating or moving the abradant so that a different area is used each time for rubbing,^(47, 91, 99) or by constant destruction and renewal of the abradant surface on removal of its debris by filtering vacuum or blower methods.^(46, 88) If finishes are present to "gum up" the abrasive surface^(45, 128) and polish the fabric, the laboratory abrasion life of such material has been found to be out of proportion to its wear life in actual service.⁽³⁾ However, it is entirely possible that material transferred to the abradant surface may promote its efficiency and thus increase the rate of wear,^(25, 149) and this has been reported recently in the case of textile abrasion testing.⁽¹⁵²⁾

The appearance of debris on the surface of the worn fabric or retention of ruptured fibers in the yarn structure⁽⁶⁰⁾ will radically modify the abrasion performance of the material,^(75, 90, 100, 169, 175) and so the general practice has called for removal of lint, and other products of abrasion by vacuum methods^(103, 152, 169, 171) or blowing,^(45, 90, 99, 106) where possible, or by intermittent brushing of the

sample. Very little provision is included in the design of abrasive machines to eliminate the effects of static electricity upon the adherence of dust, lint, and debris to the sample during test.⁽⁷⁶⁾

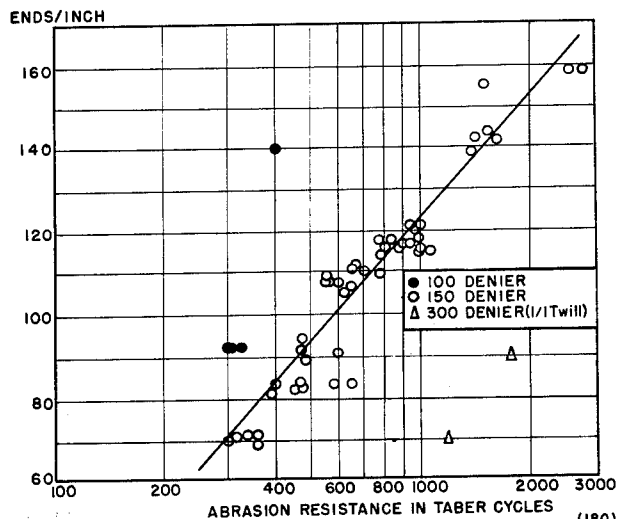
Thus it is seen that changes which occur in surface or material properties of solids in contact, will affect their relative rate of wear. Depending on the original nature of the surfaces, the lubricant material transfer, and heat of friction, the rate of damage to one or the other surface may increase or decrease as the test progresses. It is essential to observe closely the character of the surfaces before drawing conclusions as to the behavior of the abrasion rate. The problem of manufacturing uniform abrasives capable of maintaining constant abrasive surfaces during repeated tests remains as a challenge to the instrument designer.

Fig. 5
EFFECT OF WEAVE ON THE ABRASION RESISTANCE OF RAYON LININGS



NOTE: ALL FABRICS ARE MADE OF 150 DENIER, 40 FILAMENT YARN, WARP AND FILLING. FABRIC IS IN ALL CASES VISCOSE OR VISCOSE-ACETATE COMBINATIONS.

Fig. 6
EFFECT OF WARP YARN COUNT ON THE ABRASION RESISTANCE OF VISCOSE RAYON LININGS



NOTE: FABRICS ARE 2/1 TWILL EXCEPT ONE INDICATED AS 1/1 TWILL.

SOURCE - TAIT (180)

THE CONTRIBUTION OF TEXTILE GEOMETRY

INFLUENCE ON PRESSURE

Threads per Inch

It has been indicated above that frictional resistance and wear damage of elastic solids is dependent on the normal force between the rubbing surfaces, (1,12,27,31,123,149,150,199) and that pressure based upon geometric area of contact is a secondary factor. In the case of visco-elastic bodies, however, the frictional resistance and the wear damage under given conditions of normal loads, is proportional to the geometric area of contact. This fact has been demonstrated many times in both laboratory and field tests of textile materials.

It has been shown that with all other factors held constant, the abrasion resistance of warp-flush fabrics is improved by increasing the number of warp threads per inch, thus reducing the normal load per warp crown. (104,120,122,167,171) Similar effects are noted in increasing the pickage of blanket materials. (66) This same trend is observed in fabrics varying in weave and yarn diameters, (180) as is indicated in the work of Tait presented in Figures 5 and 6.

Quartermaster combat-course tests (141,183,215) have likewise shown the effect of warp threads per inch in a herringbone twill cotton work garment (Table IV). Here it is seen that the fabric with the lowest texture in both warp and filling (76 x 48) suffers significantly more wear (based on an analysis of variance) than the higher texture materials. Although there were no statistical differences among the four higher texture materials, there were good indications that the highest texture favorably affected the rate of wear and resistance to wear of Fabric 1.

Structural changes in textile fabrics often occur in use. The effect of laundering on fabric geometry is one of the most pronounced factors in this connection. Shrinkage serves to increase the number of threads per inch and thus reduce the wear rate in subsequent rubbing. (104) It follows that laboratory abrasion tests should be conducted on the fabric in that state which it will maintain over the major portion of its service life.

The importance of cohesion as applied to fiber, yarn, and fabric structures has been stressed by investigators of fabric wear resistance. (128,177) It has been held that cohesion may best be obtained by closer weaves and higher textures than by higher yarn twist, for the former conditions will permit yarn flattening and presentation of greater surface, resulting in the reduction of unit pressure

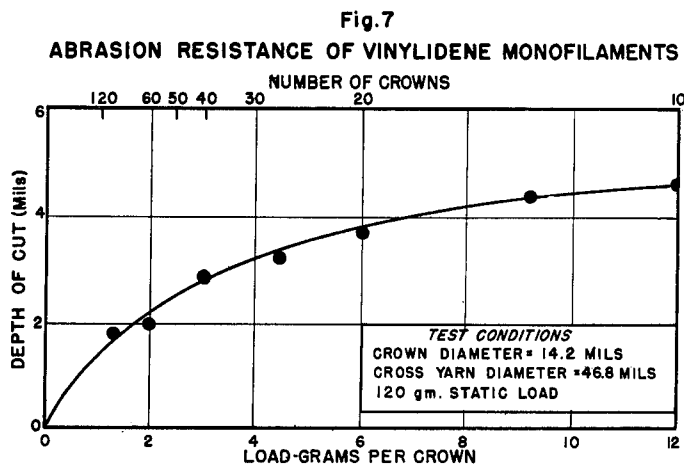
TABLE IV

Wear Tests of Fabrics Varying in Threads per Inch

Fabric	Texture W F	Yarn Count W F	Labora- tory Abrab.***	Wear Score*					
				Trouser Cycles			Jacket Cycles		
				6	8	10	6	8	10
1. HB Twill, Ctn., Greige	88 59	12.8 10.3	21	34.0	46.8	67.8	8.6	11.3	21.6
2. " "	89 49	12.8 10.3	20	40.2	49.3	68.9	8.1	11.7	23.4
3. " "	82 54	12.8 10.3	38	35.8	52.3	75.6	9.9	13.5	22.6
4. " "	77 59	12.8 10.3	26	38.5	47.3	69.5	8.6	11.8	20.5
5. " "	76 48	12.8 10.3	40	38.8	57.1	81.8	8.3	14.2	23.9

* Average based upon the wear scores of 40 garments of each fabric worn by the same men, one cycle (two traversals of combat course, followed by a mobile laundering) at a time in rotation until each garment had completed 10 cycles. (The higher the wear score, the less durable the garment.)

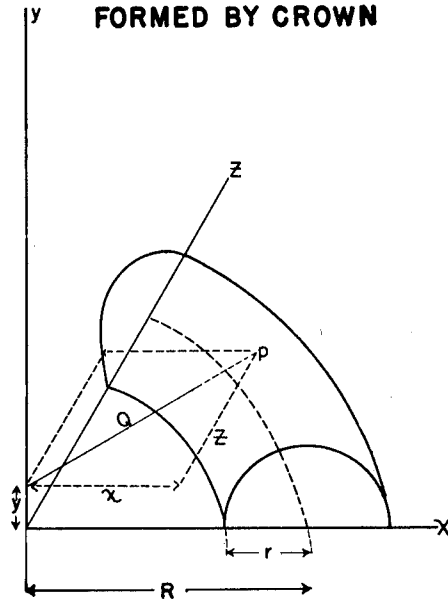
** Wyzenbeek abrasion tests expressed as per cent loss in warp strength, 250 cycles, 2 lb. load, 2 lb. tension, #0 emery paper abradant.



at any one point.(120) In order to study separately the effects of a reduction in crown pressure due to a greater number of threads per inch the behavior of monofilaments was considered as a part of the wear-resistant project at the Quartermaster laboratories. A reciprocating abrasion action was used, with emery paper as the abradant and a constant load applied to the abradant head. Varying numbers of vinylidene (14.2 mil) monofilaments were wound around a vertically

supported brass plate to simulate varied textured fabrics. The results

Fig. 8
THREE DIMENSIONAL VIEW OF TORUS SECTION
FORMED BY CROWN



plotted in Figure 7 illustrate the effect of the varying pressure per crown. The straight-line relationship reported for similar tests on solid materials is altered in this test because of the change in area of contact as the abrasion proceeds. When one considers the usual crimp diagram (See Figure 14, Page 49)(125,126) it is evident that in progressing from the front to back surface the projecting yarn assumes two separate alternating forms, that of a torus section and of an inclined circular cylinder. That portion of the yarn which is subjected to surface abrasion is torus-like and an expression can be derived for its horizontal sectional area as successive layers are removed in abrasion. Consider Figure 8, in which it is seen that the area, A , of a horizontal section (that is, in a plane perpendicular to Z axis) at an arbitrary depth, Z , equals $\int 2 y dx$ as y varies from 0 to $+r$ and x varies from $\sqrt{(R-r)^2 - z^2}$ to $\sqrt{(R+r)^2 - z^2}$. If P is taken as any point on the surface of the torus and Q is the perpendicular distance from P to the y axis, it is seen that:

$$(Q-R)^2 + y^2 = r^2$$

$$\text{or } y^2 = r^2 - (Q-R)^2$$

$$\text{and } y = \sqrt{[(r-Q) + R][(r+Q) - R]}$$

$$\text{since } Q^2 = x^2 + z^2; \quad 2Q \frac{dQ}{dx} = 2x \frac{dx}{dx}$$

$$\text{and } dx = \frac{QdQ}{\sqrt{Q^2 - z^2}}$$

$$\text{therefore } A = \int_{R-r}^{R+r} 2y \, dx = \int_{R-r}^{R+r} \frac{[(r-Q) + R][(r+Q) - R] QdQ}{Q^2 - z^2}$$

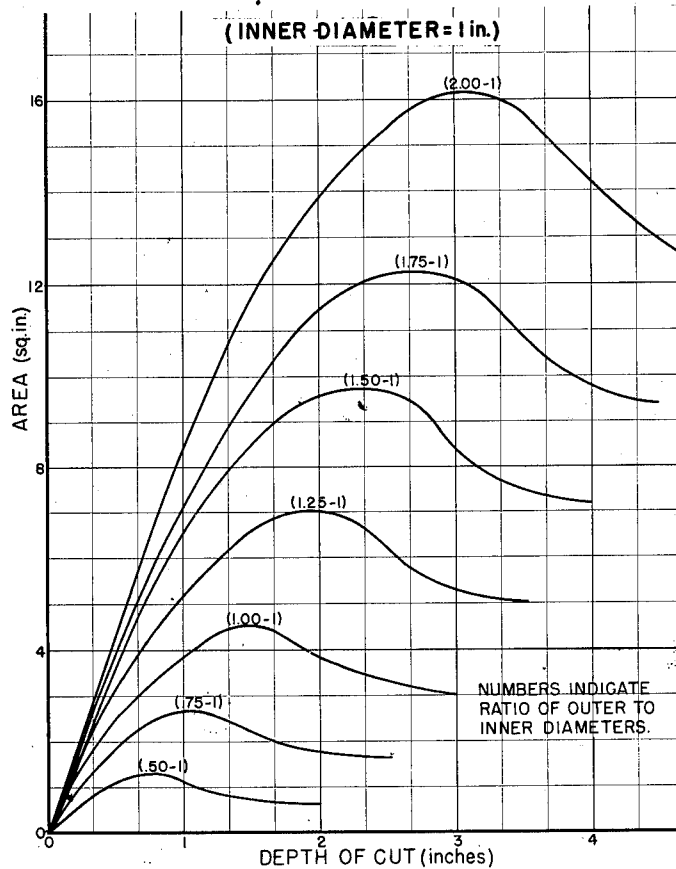
This relationship has been worked out mechanically and is presented in Figure 9 for a torus series with varying inner and outer diameters. Using these curves one can easily calculate the bearing surface on a plain weave textile fabric as its thickness is reduced in abrasion. It should be noted, however, that no account is taken here of the compressive change in geometric contact area of fabrics as a result of normal loads; this is the subject of another study. It suffices to say that the abrasion rate of textile structures will vary in accordance with the geometric area of contact and this in turn will increase in most fabrics as a consequence of wear.⁽¹²³⁾ This effect is clearly demonstrated in Quartermaster abrasion tests on monofilament yarn (Figures 10 and 12).

In conclusion, it may be stated that textiles and metals differ in their rubbing phenomena in that for a given normal load the local pressure on a fabric may be decreased by enlarging the geometric area of contact. Local pressures between metal surfaces remain constant under these circumstances. It therefore becomes possible to reduce the rate of local wear of fabric by increasing the number of abrasion-bearing yarns, flattening their crowns, or reducing yarn curvature in the initial phases of attrition.

Yarn Diameters

The association of greater wear life with increased thickness of a given material has been reported many times and implies a straight-line relationship between loss in thickness and the number of rubs in an abrasion machine.⁽¹⁵²⁾ In textiles, however, the thickness or diameter of the yarn exposed at the rubbing surface has a twofold effect.

Fig. 9
AREA OF TORUS SECTIONS



It has been shown that for a given set of balanced yarns, fabric thickness can be varied from the sum of the yarn diameters to $3/2$ the sum, while the abrasion resistance of the fabric changes only to a minor degree, indicating that the amount of fiber at the wearing surface is the second important feature. (104)

More recently, both yarn (79,201) and fabric abrasion (168,180) studies have indicated the effect of yarn diameter on abrasion life of textile materials. Tait's detailed data, plotted in Figure 6, (Page 40) show significant increases in abrasion life of lining fabrics as heavier yarn sizes are used. Quarter-master studies of cotton fatigue fabrics (3,142,219) have shown significantly longer combat-course life

of cotton fabrics with higher warp yarn counts (i.e., heavier warp yarns) since this set of yarns is subjected to the most severe wear in the herringbone-twill structure. (See Table V) Corresponding results are reported in laboratory abrasion tests.

When the effect of yarn diameter was evaluated on vinylidene monofilaments the data plotted in Figure 10a were obtained. The cycles corresponding to the end point of other types of yarn abrasion tests are represented by the lowest recording on each of the curves for the 5.1, 8.2, 10.4, 12.4, and 14.2 mil diameter monofils. These tests had been conducted with a 120-gram load on 16 crowns, wound and abraded as indicated above. (177) In a second experiment the abrasive load was reduced (by increasing the number of crowns) so as to increase the sensitivity of the abrasion test and permit a study of the rates of wear on the monofilaments. Data of the second test are plotted in Figure 10b and represent the depth of cut vs. abrasion cycles rather

Fig.10
EFFECT OF YARN CROWN DIAMETER ON ABRASION
RESISTANCE OF VINYLIDENE MONOFILAMENTS

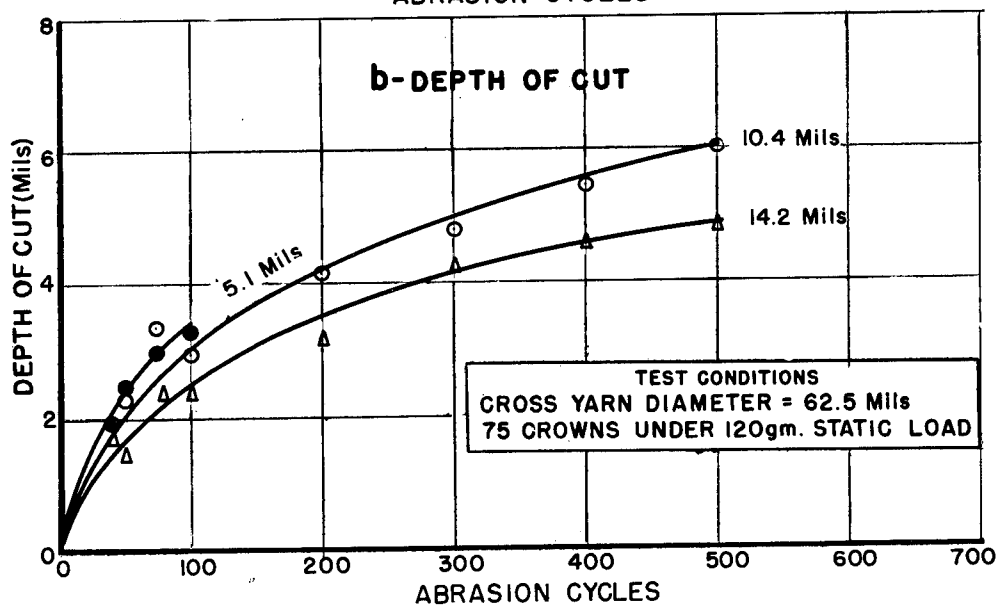
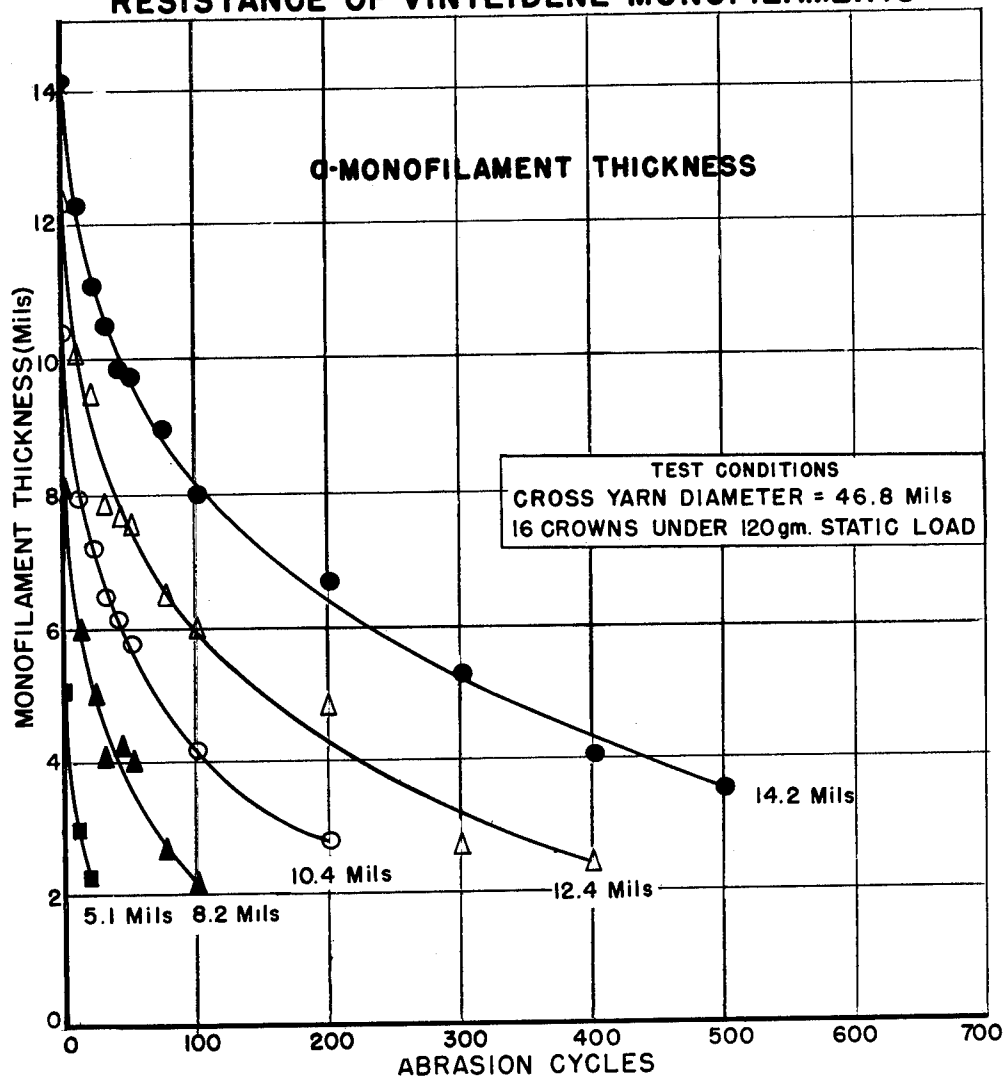


TABLE V

Wear Tests of Fabrics Varying in Yarn Count(142)

Fabric	Texture		Yarn Count		Labora- tory Abrab.**	Wear Score*					
	W	F	W	F		Trouser Cycles			Jacket Cycles		
						6	8	10	6	8	10
1. HB Twill, Ctn., Greige	76	57	10.9	8.8	20	8.5	14.0	21.7	4.2	6.8	11.1
2. " "	77	60	10.9	11.9	19	6.7	10.2	17.8	3.1	5.0	7.5
3. HB Twill, Ctn., OD #7	78	50	13	10	--	9.0	15.8	25.9	8.1	10.1	14.5
4. HB Twill, Ctn., Greige	76	60	14.6	8.8	23	12.7	19.5	33.4	5.8	10.6	20.9
5. " "	80	61	14.6	11.9	23	10.3	21.0	37.4	7.4	12.8	18.7

*Average based upon the combat-course wear scores of 34 garments of each fabric worn by the same men, one cycle (two traversals of combat course followed by a mobile laundering) at a time in rotation until each garment had completed 10 cycles. (The higher the wear score, the less durable the garment.)

**Wyzenbeek abrasion tests expressed as per cent loss in warp strength, 250 cycles, 2 lb. load, 2 lb. tension, #0 emery paper abradant.

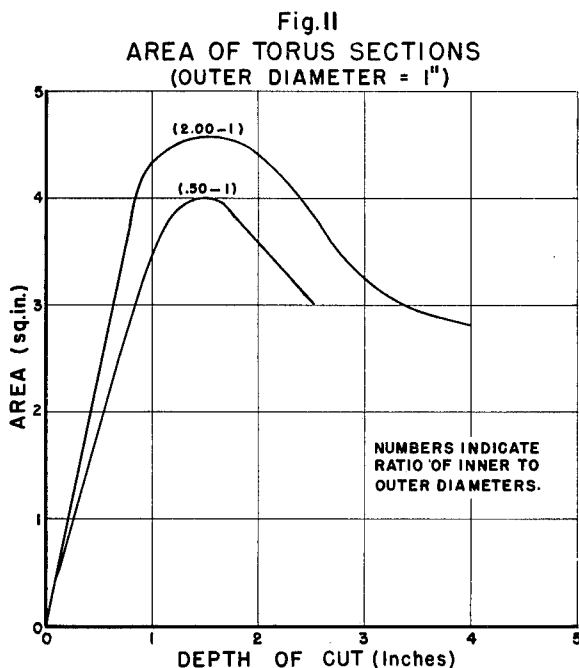
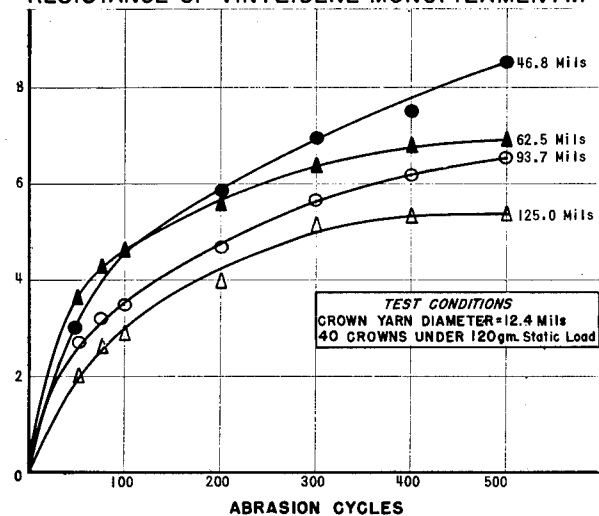


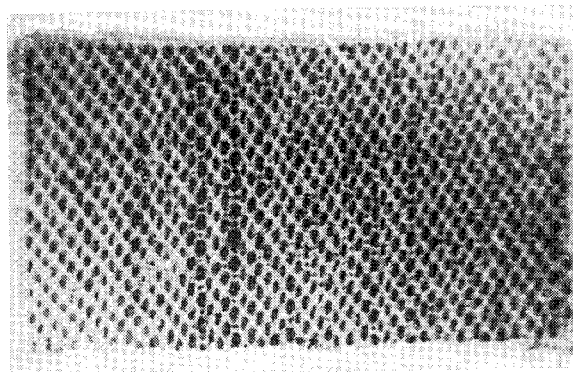
Fig. 12
EFFECT OF CROSS YARN DIAMETER UPON ABRASION
RESISTANCE OF VINYLIDENE MONOFILAMENT...



than the remaining thickness of the monofil. Here the influence of yarn diameter on the rate of wear is clearly indicated, resulting from differences in sectional areas (See Figure 9) and therefore local pressures at points of contact.

Parallel experiments were conducted using a constant (12.4 mil) diameter crown yarn and modifying the radius of curvature of the bent crown (corresponding to the radius of the cross yarn (or $R - r$ in Figure 8)). Here again differences in sectional areas of contact may be expected from the yarn geometry. This is seen in Figure 11 in which areas of the torus sections are plotted against depth of cut for constant diameter crown yarns but with varying cross-yarn diameter. The results of the abrasion tests with varying cross-yarn diameters are plotted in Figure 12. Again the influence of sectional areas on rate of abrasion is demonstrated.(94)

Fig.13
SURFACE CONTACT OF A COTTON SATEEN UNDER
PRESSURE.* DIFFERENCES IN COMPRESSION DUE
TO UNEVEN YARNS
(Mag.4x)



*** 8.2 lbs. EXERTED WITH A HARD BACKING AGAINST A SAMPLE
1.0 BY 0.5 INCHES**

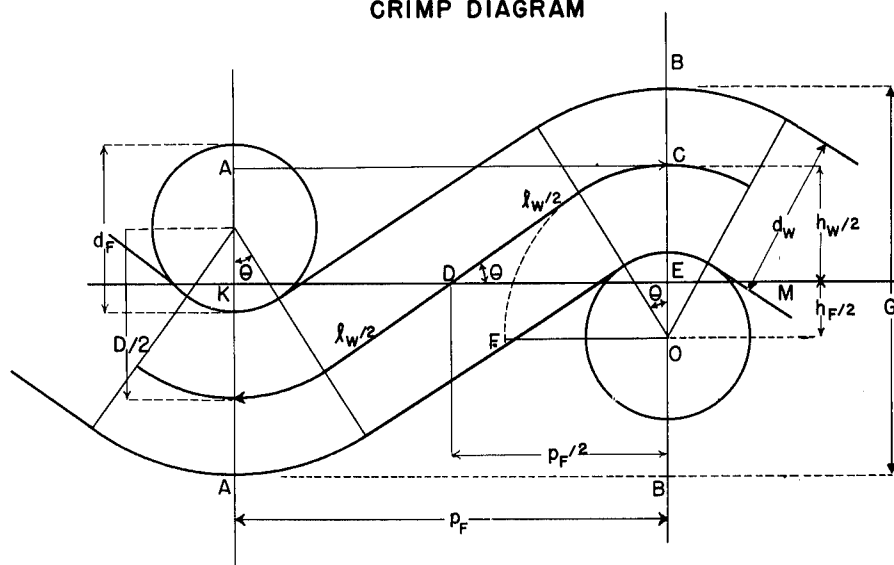
It should be emphasized that large diameters of the abrasion-bearing yarns must be accompanied by uniformity if increased wear life is desired. Unusually heavy yarns serve as focal points in fabric degradation due to the high pressure concentrations set up. This is clearly indicated in Figure 13 which pictures the contact areas of a cotton sateen pressed against a piece of ground glass under a load of 16.4 pounds per square inch.(94) The heavy filling yarn here is under greater pressure than the other yarns and so has been flattened to a greater extent. Its larger diameter has meanwhile brought the warp yarns crossing it to the surface, subjecting them to early damage.

Thus it has been shown that geometric area of contact between abrasive surfaces and textile fabrics can be increased by use of larger diameter warp and/or filling yarns. As a result local pressure is reduced, and with it wear damage.

Crimp Distribution

Crimp distribution determines the relative vertical displacement of each set of yarns above and below the plane of the fabric. As defined in studies of cloth geometry, (125,126) true crimp, c , is the ratio of the difference between the axis length of a yarn, l , and its horizontal projection, p , to the horizontal projection (Figure 14).

Fig14
CRIMP DIAGRAM



Crimp is usually determined by measuring the difference between the yarn length in the fabric and the length of the yarn when withdrawn and its waviness removed by light tension and expressing it as a per cent of its horizontal projection in the fabric. In the case of plain weaves, true crimp, as related to each intersection, can thus be determined. However, to compute true crimp for twills and sateens, measured crimp must be multiplied by a weave factor, M , which is determined from the weave pattern. For one set of yarns M is the ratio of crossovers of that set per repeat to the number of perpendicular threads per repeat. Thus from consideration of the constructional formula, e.g.

Twill construction (1 to the right)

$$\frac{5}{5}$$

$$\frac{10}{2} = 5.00$$

$$\frac{3}{2}$$

$$\frac{5}{2} = 2.50$$

$$\frac{4}{2} \frac{1}{2}$$

$$\frac{9}{4} = 2.25$$

It is seen that the sum of the vertical displacement of any yarn system, h , and its diameter, d , will determine the yarns which project at the rubbing surface of the fabric, and therefore will be subjected to maximum damage in abrasion. (93, 118)

The expression relating yarn displacement, h , to true crimp, c , and yarn spacing, p

$$h_1 = \frac{4}{3} p_2 \sqrt{c_1}$$

(Subscripts 1 and 2 refer to warp and filling values respectively.)

has been found to apply over a wide range of fabric structures. (125, 126) For more exact values of h , a graphical model has been suggested to establish the mutual dependence of p , h , and l , all of which are expressed in terms of the average yarn diameter - $\frac{D}{2}$ or $\frac{d_1 + d_2}{2}$.

The model reproduces the actual yarn geometry shown in Figure 14. It consists of a plywood quadrant of radius OC which is placed in position OCF . CA serves as the P_f abscissa and is marked off in units of OC starting with point C as the zero value and increasing towards A . The ordinate is marked off along the line CO in units of OC , with C as zero point and increasing towards B ; this serves as the h_w axis. A steel tape marked off in units of OC is wound around the quadrant, having been fastened at C , its zero point, and is held taut in the direction of D . Consideration of the geometry involved will demonstrate the utility of the unit described to determine $h_{w,f}$ when d_{wf} , P_{wf} , and C_{wf} are given. The tape is wound around the quadrant and held taut at its unfastened end until the given value of l (in $\frac{D}{2}$ units)

cuts the p abscissa (value of p expressed in units of $\frac{D}{2}$), whereupon the corresponding magnitude h , also expressed in units of $\frac{D}{2}$, is read directly from the graph.

More recently a surface coefficient, K_n ,⁽⁶⁰⁾ has been proposed to establish the protruding yarn system based upon the fabric geometry. Here

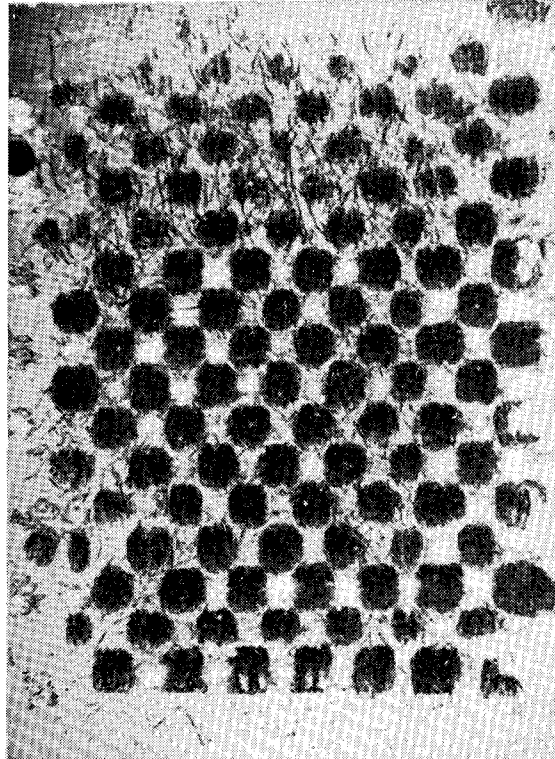
$$K_n = 0.667 \frac{n_o \sqrt{N_o}}{n_y \sqrt{N_y}}$$

where n_o and n_y are the fabric densities in warp and filling directions respectively and N_o and N_y the corresponding warp and filling yarn numbers. Thus if K_n is less than 1.0 the warp threads protrude at the surface of the fabric and if K_n exceeds 1.0 the filling is exposed. When K_n equals 1.0 the crowns of both yarns lie in the plane of the fabric surface.

In studies of plain weaves possessing high warp and low filling crimp the curve showing warp strength vs. abrasion cycles demonstrates a steep slope indicative of a high rate of damage, while the filling-strength curve is quite flat until the warp is almost entirely worn away.^(43,90,103) In similar studies carried out recently under Quartermaster auspices⁽⁸⁸⁾ dealing with twill, sateen, and herringbone-twill weaves negligible wear damage is noted in yarns which are buried below the rubbing surface, and conversely, maximum abrasion takes place on the surface yarns. Visual evidence of the extent to which damage can occur to one set of yarns while the other remains relatively untouched is presented in a photomicrograph of a horizontal section of an Army poplin material (Figure 15). This photograph demonstrates the extent of warp damage which may occur with no effect upon the filling yarns. The usefulness of such horizontal sections in studying fabric geometry as related to abrasion resistance has been amply demonstrated.^(93,130)

With the importance of crimp distribution established, it is conceivable that the abrasion characteristics of a fabric can be significantly changed by any factor which will modify the crimp balance. Comparison of fabrics in the loom state with high warp crimp vs. the finished state in which the warp crimp has been significantly reduced have shown significant difference in abrasion performance. Laundering of the finished fabrics and subsequent shrinkage similarly cause crimp and therefore abrasion action changes,^(103,104) but here account must also be taken of the increased number of threads per inch. Finally, slight modifications in fabric construction or weaving conditions, e.g., reed width and warp tensions, may significantly alter the surface of a fabric and its abrasion performance.⁽⁴⁰⁾ In effecting crimp changes through control of "in-loom" construction or weaving and finishing conditions one must have full cognizance of the geometric limitations involved as a result of yarn jamming,^(125,126) and the physical

Fig.15
HORIZONTAL SECTION OF ARMY POPLIN
(Mag.18x)



limitations imposed by inherent yarn properties, particularly stiffness. Abrasion experiments have illustrated the importance of this requirement. In one case, (104) fabrics were constructed with high filling and low warp crimp, resulting in great damage to the filling in wear and little damage to the warp. In slightly modified constructions the warp texture was increased, resulting in greater filling crimp. The experimental series was extended until the jamming point was reached, beyond which warp texture increases simply reduced filling crimp. Just before the jamming point protection to the warp yarns was noted to be highest. The protection of the filling yarns, on the other hand, was not at a minimum at this point for their twisted structure tended to rupture long before the final fiber was worn away, but the effect of twist will be discussed later. In another instance, (43) increased warp tensions in weaving were not sufficient to overcome the jamming which occurred in the constructions selected for study, and weaving conditions were not found to significantly affect wear resistance. In still another case, it has been found advantageous

to reduce filling texture so as to enhance warp crimp, thus protecting the loosely twisted filling from surface abrasion.(93)

In few instances will tension during an abrasion test or during the wear life of a fabric be sufficient to alter the crimp balance in the material.(43) However, wherever the stresses are of sufficient order to reduce crimp in either direction modified abrasion results may be expected. This is particularly true in novelty and fancy fabrics where long floats at irregular intervals cause a maldistribution of tensile stresses, or where ribs occur, or where intermittent heavy yarns in warp and filling cross one another and create projecting crowns.(131) Thus, it may be expected that a fabric which does not possess over-all dimensional stability will give trouble in laundering, pressing, and subsequent wear.

It is interesting to note that where bursting strengths are used as a measurement of wear damage, crimp distribution affects both abrasion damage and its measurement. In one case reported(47) of a low warp, high filling crimp sateen, bursting strength was found to be a measure of damage in only one system of threads, the low-crimp warp. Thus, when wear took place on the side where the warp was protected by the high-crimp filling, little loss in bursting strength was noted, and vice versa.

In summary, it may be said that crimp distribution will determine the degree of yarn projection at the rubbing surface and therefore the extent of damage to each system. Factors which affect crimp will in turn modify the wear behavior of textile fabrics. In designing wear-resistant fabric it is essential to consider the desirability of uniform projection of both yarn systems. Factors which control such projection include relative yarn diameters, stiffness of the fibers, reed spacings, threads per inch, weaving tensions and finishing tensions. It should be recognized that the controlled projection of one set of yarns is often desirable.

Weave as it Influences Projection

In a balanced-yarn plain weave fabric constructed with high warp cover, anywhere from $K = 20$ to $K = 30$, the warp threads will bend about the filling threads and little opportunity will be afforded for filling crimp to occur. Even when extra-width reeds are used and the material is subjected to high tensions in the loom or in subsequent finishing procedures, the jammed condition(125) is reached before any measure of crimp redistribution takes place and the warp remains projected on the surface of the fabric. This is particularly true in tightly woven poplin(197) constructions (Figures 2a and 15) where the

filling yarns are heavier than the warp, resulting in greater resistance to bending of the former. In such cases the warp thread projects significantly on both face and back of the fabric (Figure 15), as is pictured in the ideal crimp diagram of Figure 14.

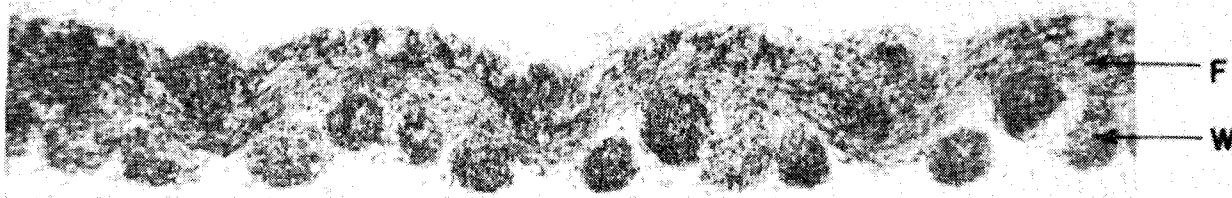
Where twills or sateens are considered it becomes evident that many of the assumptions of the simplified cloth geometry no longer apply. The longer the float, the less the restraint on the yarn system. Here yarns are no longer restricted to alternating from one side of the fabric to the other, but bend sideways and allow for the closer packing characteristic of twills and sateens. In particularly long floats, such as are found in the Army five-harness sateen(193) the torus-cylinder form of alternating yarns is modified and a general arc-like form is assumed. This, when combined with a tendency of adjacent yarns to override one another (See Figure 16a), results in higher projection of the yarn system containing the greater number of floats on each side of the fabric - despite the distribution of crimp. This tendency is used to good advantage in protecting from surface abrasion the system of yarns which bears the major stresses during service. In Army utility garments it has been observed that the longitudinal yarns, normally the warp, bear the major stresses during combat or fatigue activity of the wearer.(87) Damage to the warp is further effected by the relative direction of the yarn twist and of the twill,(171) the more pronounced twills suffering earlier loss in strength.

Based upon the number of holes caused by failure of filling as against warp, Quartermaster tests have shown that the filling-flush sateen(193) offers the maximum protection(135) to warp threads during wear over the combat course. In one such test(139) several different weaves were evaluated and it was shown that herringbone twill,(194) denim,(193) and oxford(196) showed the greatest hole formation due to surface wear when the garments were designed with the warp floats exposed to the rubbing surface. In the case of herringbone twill and sateen arranged so that the filling floats were exposed, filling damage was three to six times that of the warp in the herringbone twill and fifteen to twenty times that of the warp in the sateen. In short, the sateen showed least warp damage of all fabrics tested.(139) When cross sections of the fabrics in question are observed (Figure 16) the additional protection afforded the warp by the longer filling float of the sateen becomes evident.

Laboratory tests (88) conducted on sateen,(193) herringbone twill,(194) and uniform twill(195) with reciprocating and rotation-type abrasion machines have consistently shown the sateen structure to furnish maximum warp protection when the filling floats are subjected to rubbing. No reversal in this tendency was noted as a result of change in abrasion direction. Conversely, maximum damage occurred to the filling

Fig.16
GROSS-SECTIONAL VIEWS OF VARIOUS COTTON
FABRICS USED BY THE ARMED SERVICES
(Mag.32x)

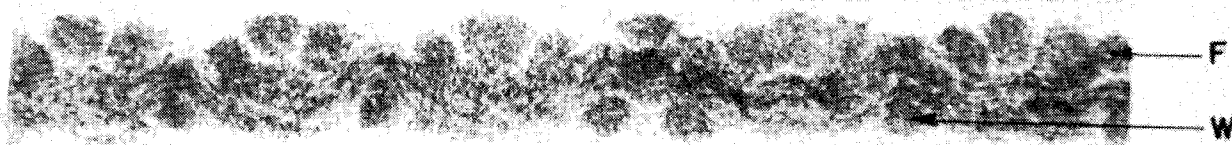
a-SATEEN (ARMY)



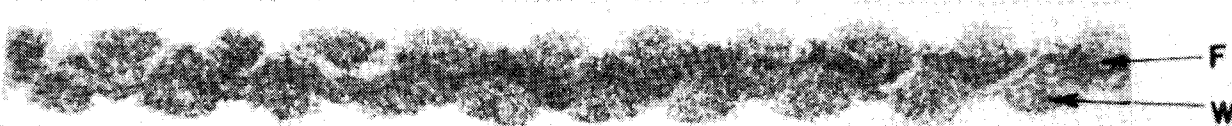
b-HERRINGBONE TWILL (ARMY)



c-HERRINGBONE TWILL (MARINE CORPS)



d-POPLIN (ARMY)



e-DENIM (NAVY)

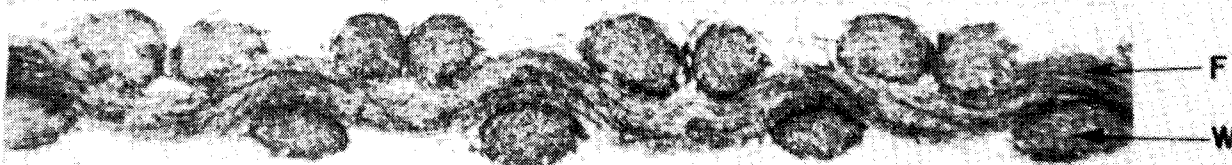


Fig.17
ABRASION DAMAGE TO SATEEN WORN FILLING FLUSH
(Mag.10 x)

ABRADED



UNABRADED



floats of the sateen weave. This is demonstrated in the surface photomacrograph of Army sateen shown in Figure 17. When warp floats are exposed on the rubbing surface it is again seen that the longer floats suffer greater damage, (171,180,212) e.g., in the tests on 4/1 sateens, 2/1 twills, and 1/1 taffetas (Figure 6, Page40).

It has thus been shown to be characteristic of the five-harness sateen that the warp yarns project on one surface and the filling yarns on the other. In tightly woven, high warp-cover plain or oxford weaves the warp yarn projects on both face and back and is subject to damage as shown in Figure 2 (Page 24), regardless of the surface abraded. In the Army twills and herringbone twills the warp yarns project on the face but are almost flush with the filling floats at the back. The latter anomaly is explained by reference to the relative float lengths of the projecting yarns, for it is evident that the longest float will balloon out to the greatest extent. Measurements of float length in the above experiments(87) are presented in Table VI. Here it is shown that the back of the sateen construction has the longest filling float and the highest ratio of filling to warp floats.

TABLE VI

Float Lengths of Selected Army Fabrics(88)

		<u>Warp</u> (mm)	<u>Filling</u> (mm)
<u>Twill</u>	Face	0.95	----*
	Back	0.26	0.53
<u>Sateen</u>	Face	0.74	----*
	Back	0.26	0.74
<u>Herringbone</u> <u>Twill</u>	Face	0.90	0.26
	Back	0.53	0.58

* Not discernible in photomicrograph

More recently comparison between the several fatigue fabrics of the various services has further demonstrated the influence of weave and float length on yarn projection and relative protection of the two systems from surface abrasion. Two herringbone twills were evaluated here, one with a float of two,(194) the other with a float of three.(198) The other fabrics were a five-harness sateen and a 2/1 denim construction. Details on these fabrics are furnished in Appendix Table I. In Table VII below, it is seen that all the twills lose significantly in warp breaking strength after reciprocating warpwise rubbing. However, when the fabrics are reversed the sateen, with the maximum filling float length, is the only material which demonstrates almost complete warp protection under the conditions of abrasion used. This is borne out in Figure 16, where the role of float length and weave in determining yarn displacement becomes very evident.

It has been shown(177) that flex abrasion most nearly correlates with combat-course results on the fabrics described in Appendix Table II, for here the abrasion is directed along the warp and the sample reaches the endpoint when the warp strength is reduced below the point of the tensile load applied during the test. The flex-abrasion results of Table VII for the back of the fabrics again demonstrate the amount of protection afforded the stress-bearing warp yarns by the filling.

TABLE VII

Laboratory Abrasion Tests on Cotton Fatigue Fabrics

Fabric	Float Length		Wyzenbeek Abrasion*** % Loss in Warp Strength		Flex Abrasion**** Cycles When Abraded	
	Warp*	Filling**	Face	Back	Face	Back
Sateen (111)	.0635"	.0476"	--	0	--	2029
Herringbone Twill 2/1	.0434"	.0263"	12	6	646	1315
Herringbone Twill 3/1	.0600"	.0288"	19	9	595	1255
Denim	.0426"	.0286"	23	--	1784	--

* On warp flush side (computed).

** On filling flush side (computed).

*** Wyzenbeek Precision Wear Test Meter, (184) 2 lb. load, 2 lb. tension, abraded warpwise, 250 cycles.

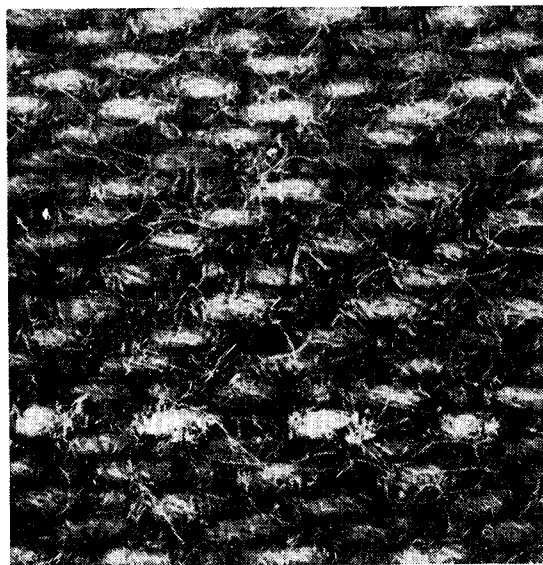
**** Stoll-Quartermaster Abrasion Tester, (177) warpwise flex abrasion with folding bar, 4 lb. pressure, 4 lb. tension, 1 inch wide warp strips, end point cycles to rupture.

As a final point, it should be stressed that irregularities in the weave pattern should be avoided to prevent one portion of the repeat from projecting above the other and receiving the brunt of the wear. An example of this is seen in the herringbone-twill fabric(194) which at one point in the repeat reduces the length of the filling float by 50 per cent. This throws the warp thread, crossing the filling at this point, out of the plane of the fabric surface and subjects it to excess wear at an early stage, as is evident in Figure 18a. At another point in the herringbone twill, where a filling float is increased 50 per cent causing it to arch out of the plane of the back surface of the fabric, maximum wear is again noted (Figure 18b).

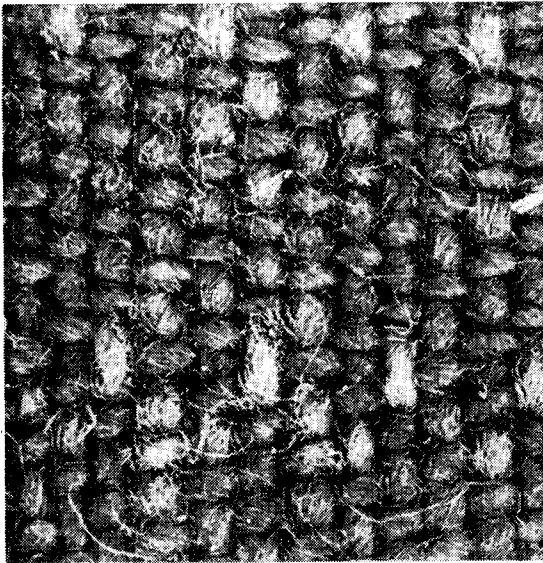
In summary, the three-dimensional aspects of the fabric surface are seen to have an important influence on the wear life of any woven system of threads.(94) The desirability of protecting the stress-bearing elements of cloth structures in service has been emphasized. Weave is

Fig.18
 ABRASION OF PROJECTING FLOATS OF HERRINGBONE TWILL
 (Mag.10x)
ABRADED

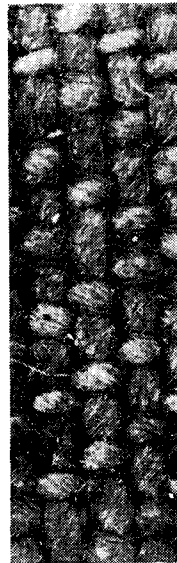
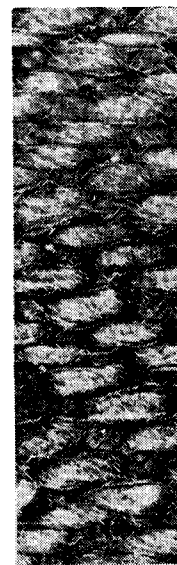
α -FACE



b-BACK



UNABRADED



a versatile efficient method of so doing for it permits control of float length, a key factor in determining yarn projection in high-cover fabrics. Uniformity of pattern is essential lest isolated projection points develop leading to early attrition because of localized normal abrasive pressures.

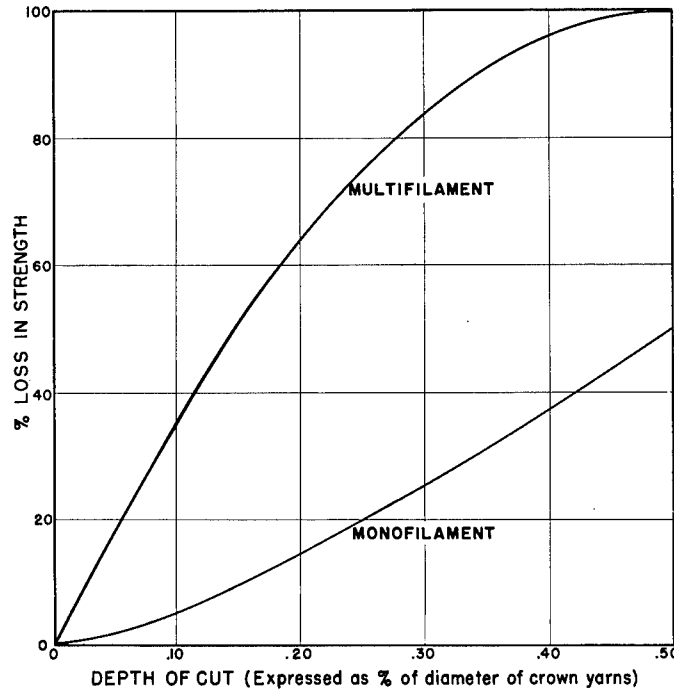
Twist as it Influences Contact Area

The importance of cohesion of fiber, yarn, and fabric has been stressed by many investigators of the wear phenomenon.(128,177) It has been shown the surface wear of fabrics can consist of fiber damage with either partial or complete rupture of the individual hairs, or a whole plucking of the fiber from the yarn structure.(43,212) For good wear the tearing-out action can be reduced by a firm binding of the fibers.(113) This binding may be accomplished by increasing yarn solidarity with higher twists, or by use of tighter weaves.(149) When twist multiples are increased from 1.5 to 2.3 in the yarns of linen fabrics, an increase of 15 per cent in abrasion resistance has been reported,(104) and it was thought that the harder, more highly twisted yarns had less contact with the abrasive surface and so suffered less damage at the surface fibers. Based upon the results of more recent yarn tests, it would appear that lower twists afford poor fiber binding while high twists stiffen the yarn to a point where very little contact is had between yarn and abrasive. This in turn results in high local abrasive pressures and early breakdown of the yarn structure. However, when materials are laundered to a greater extent than abraded, the poor fiber binding of low twist yarns plays a major role in causing early breakdown. Here higher yarn twists are more durable.(67) In the experiments with viscose materials(79) an optimum twist is recorded beyond which increases in the number of turns per inch result in lower abrasion resistance. Here the curves of abrasion resistance vs. twist follow the pattern of the well-known, tenacity-twist curves.(132) It is seen therefore that the compressional characteristics of a yarn and its cohesiveness play dual roles in determining abrasion resistance as its twist is altered. It follows that different abrasion behavior may be expected in fabrics of varying yarn twists, depending upon the normal loads between the rubbing surfaces.

In considering endpoints twist becomes a significant factor in determining the loss in yarn strength which may be expected for a given depth of cut at the crown of a yarn float. Yarn twist will bring different fibers to the surface in any float length. The number of different fibers at any surface will depend upon the float length, the turns per inch, and the fiber and yarn diameters.(132,158) In many instances all the fibers lying at a given depth (abraded depth of crown) from the yarn surface rise to the surface at each float or at

Fig.19

RELATIONSHIP BETWEEN DEPTH OF CUT & % LOSS IN STRENGTH OF MULTIFILAMENTS & MONOFILAMENTS



adjacent floats, thus degrading yarn strength by an amount proportional to their cross-sectional area. When this loss is compared to the loss of strength at the same depth of cut in a monofilament yarn, the relationship plotted in Figure 19 is seen. It is further noted that the strength loss of the monofilament is in effect directly proportional to the volume of yarn removed and therefore to the loss in weight during abrasion. In fabric-abrasion tests these same relationships have been observed between loss in weight of the specimen and loss in strength.(43)

It is concluded that yarn twist affects abrasion resistance through the media of its influence on fiber binding, yarn hardness and distribution of damage through the cross section of a yarn crown. Yarn twist vs. wear resistance curves follow the pattern of twist-tenacity curves but there is no evidence that optimum twist for wear and strength coincide. Again the condition of wear will determine the balance of requirements between protection from fiber snagging and from high abrasive pressures. Optimum twists will therefore vary according to this balance.

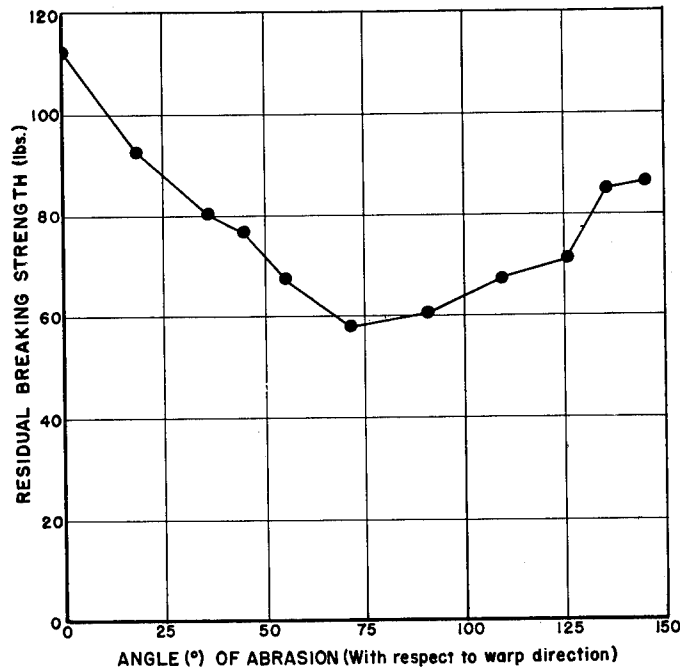
DIRECTION OF ABRASION

As Related to Yarns

Major differences exist in the abrasion performance of textile fabrics when the direction of rubbing is altered with respect to warp and filling coordinates.(104,166) The advisability of analyzing field wear to establish the predominant direction of wear and stress has been noted in early abrasion studies.(43,93) In experiments where fabrics have been rubbed in warp and filling direction, as high a ratio as 2:1 has been observed in the number of strokes required to form a hole.(47) Generally, the yarns which project on the rubbing surface of the fabric will suffer greatest damage when abrasion takes place in a direction perpendicular to their float lengths.(77,88,118,167) (See Figure 20) Where it is evident that abrasion and tensile stresses occur in one direction, it becomes desirable to increase the perpendicular set of yarns as to frequency and diameter and bring them to the surface to absorb the wear.(87) Under these conditions, unfortunately, the cross yarns will absorb maximum damage during a period of rubbing. Where abrasion and stress take place in opposite directions, maximum wear resistance will be achieved when the non-stress-bearing yarns are presented at the rubbing surface with their floats running in the direction of rubbing.(118) Since the direction of service wear and stress is often the same, the maximum abrasion life of the fabric will not always be realized. Wherever possible, however, the design of the garment or lay of the fabric in the pattern should be altered so as to eliminate perpendicular rubbing of the surface yarns during the wear life of the item. This matter is done more easily in the manufacture of fatigue garments for Army use than in dress uniforms or civilian clothing. One feature that can be modified quite easily is the exposure of face or back of the material to the rubbing element depending on which side exposes the non-stressed yarns. Fabric reversal of this nature is resorted to in a number of Army garments.

Mention has been made of the two types of breakdown which occur in fabric wear,(118) the loss in internal cohesion of the fiber and structural cohesion between fibers. The relative occurrence of these two phenomena depend to a great extent on the structural compactness of yarn and fabric, and upon the direction of abrasion with respect to the surface yarns. Abrasion directed along the yarn in tight, sharp-knuckled fabrics often results in a great many sheared fibers as has been shown in Figure 2a (Page 24). Abrasion directed across these same yarns tends to snag the fibers, leaving a hairy surface after a few rubs as shown in Figure 2b. Studies conducted in the Quartermaster laboratories on weaves of different float lengths demonstrate varying degrees of damage on warp and filling yarns depending on the nature of yarn projection, the float length, and the direction of abrasion. Abrasion in this case

Fig.20
EFFECT OF DIRECTION OF RUBBING ON THE ABRASION
RESISTANCE OF ARMY POPLIN (193)



has been very slight so as to permit microscopic evaluation of the initial stages of surface wear before the destruction progresses to a point where it is impossible to distinguish between the types of mechanical breakdown and to assign damage to specific yarn systems. To extend the usefulness of this technique it is of course necessary to study surface disturbance on fabrics whose structures have been brought to equilibrium in laundering. Another technique used to good advantage in studying surface structure of Army fabrics is the three-dimensional photography or vectograph process.

Direction of cutting forces has a great deal to do with the severity of shearing damage of a tool edge and extensive formulae have been worked out to account for contact angle and the frictional forces developed during chip formation.(58) In the case of textile surfaces surface roughness is accentuated by fiber and yarn geometry, while "tool angle" is more or less a random quantity due to nonuniform orientation of the abradant particles or edges.(57) It is therefore necessary to neglect "tool angle" and deal with contact angles as determined by yarn and fiber geometry.

Assuming for the moment that mechanical wear takes place with no externally applied pressure between abradant and specimen, one sees that the abrasive particle which approaches the yarn surface in a horizontal plane exerts on it tangential and normal components. The ratio of these vectors is determined by the curvature of the thread at the point of contact; the curvature is in turn dependent upon the angle of approach (in the plane of the fabric). An approach perpendicular to the yarn axis will encounter a radius of curvature equal to the yarn radius, r (Figure 9, Page 45); approach along the yarn axis will establish a contact curvature equal to the sum of the diameter of the surface yarn and the radius of the underlying cross yarn $\sqrt{(R + r)}$ in Figure 9, Page 45, and $(.5 d_f + d_w)$ in Figure 14, Page 49. The smaller the radius of curvature the larger will be the stress component normal to the yarn surface, which determines the penetration or shearing force. Since R is a positive quantity, an abrasive particle travelling in a direction perpendicular to the thread axis will cause greater damage to a projecting crown than a stroke along the yarn axis. The relative attrition resulting from abrasive action parallel to and perpendicular to yarn direction is therefore dependent to some degree on the ratio of thread diameters warpwise and fillingwise. This fact assumes importance in dealing with fabrics of a twill or sateen weave where one set of yarns projects above the other.

As Related to Fibers

The direction of fibers as they lie in the yarn will have some effect on the abrasion behavior of the material. The snagging of the fibers of twisted yarns when abraded perpendicular to the float lengths will be reduced on two counts: (1) tendency of the abrasive particles to ride along the fiber length due to reduced contact angle caused by twist helix (explained above for yarns), and (2) increased fiber-to-fiber friction in the yarn itself. This has been indicated to a limited extent in recent abrasion studies (79,132). However, it was shown that with further increases in yarn twist, reduction in abrasion resistance was noted, due it was thought to an increasing component of the fibers in the direction of the abrasion wheel path. It is difficult, however, to consider twist without taking into account the importance of yarn flattening. (103,212) This study is being extended at the Quartermaster laboratories on fabrics previously described. (3)

Another way of reducing contact angle between fiber and abrasive is by increasing the diameter of the individual fibers or filaments. However, the corresponding increases in yarn (79) and fabric abrasion resistance (Figure 7, Page 42) (47,180) cannot be

disassociated from the effects of the increased thickness to be worn before rupture, the increased strength to resist rupture, the increased contact area to resist snagging, and the increased bearing surface to reduce local abrasion pressures as discussed above in the case of yarns.

As Related to Molecular Orientation

Stress-strain properties of high polymers vary with the degree of orientation in the material. As polymeric films are stretched beyond the yield region directional orientation takes place which promotes entirely different strain behavior for stresses applied along the direction of orientation as compared to perpendicular to it. Still further, it has been shown that films which have been permanently set in one direction and held at that extension, display still different strain behavior when stressed at right angles. The latter case is comparable to the cross-fiber abrasion incurred so often in fabric service.

Considering the effects of the mechanical properties of a solid upon its frictional behavior and abrasion resistance, one would expect the abrasion resistance of an anisotropic material to vary with the angle of abrasion (ruling out macroscopic geometry). This feature is indeed difficult to evaluate in fibers because of the small dimensions involved and the geometric ratios between fiber length and diameter. Stress-strain studies on textile fibers have been concerned for the most part with tensile behavior,^(92,110,112,113) although some work has been reported recently on shearing,⁽⁶²⁾ torsional,^(37,111,119,127,129,174) and bending properties.^(36,188) Differences in directional moduli, breaking strength, and yield points are the rule rather than the exception in anisotropic textile fibers, not only because of fibrillar and molecular orientation but also because of fiber morphology,⁽¹⁰⁵⁾ as in the case of wool fibers whose torsion and bending differences are attributable to difference in components at the medulla and cuticle of the hair. It is, in fact, this difference that causes many fibers to behave as they do in helical yarns. The differences in directional stress properties which appear to be closely related to abrasion resistance are shear strength⁽⁶⁵⁾ and initial (tensile) Young's modulus, for it is seen that movement of abrasive particles across the fabric surface will, through friction or micro snagging, transmit stress components along the axis of the fiber - whether abraded parallel or perpendicular thereto. When sharp abrasants are in use shear stresses are much more localized (at one point of the fiber surface) and therefore can exceed the tensile stresses which in transmission may be distributed over the entire cross section. In addition, support of the yarn structure at point of contact can prevent further transmittal of axial tensile stresses while setting up increased shear stress in the fiber pressed between the yarn and the abrasive particle. On one hand, low

initial modulus of the fiber will allow it to give before the impact of the abradant edge while high shear strength will provide increased resistance to transverse rupture of sections of the fiber. Thus it is seen that the shear factor of metal wear⁽⁵⁷⁾ must be modified to account for tensile behavior of the fiber. Taking reported values of shear tenacity⁽⁶²⁾ in gms./den. and initial Young's modulus in tension⁽¹¹³⁾ in gms./den., one can roughly rate the abrasion quality of textile fibers by computing a ratio of the shear tenacity squared to initial Young's modulus as follows:

TABLE VIII

Relative Directional Properties of Textile Fibers

Fiber	Shear Tenacity ⁽⁶²⁾ gms./den.	Initial Young's ⁽¹¹³⁾ Modulus gms./den.	$\frac{(\text{Shear Ten.})^{(38)}}{(\text{Init. Young's Mod.})}$ gms./den.
Nylon	1.27	30	.0538
Silk	1.31	85	.0202
Cotton	0.96	55	.0167
Acetate	0.65	31	.0136
Viscose	0.72	65	.0080

The similarity between these ratios and the relative durability values shown on Page 33 is striking. It is noted that many of the German studies of fiber wear indices in emphasizing the value of knot shear strength rank these materials in a similar manner.^(14,16,154) No claim can be made for the adequacy of such an approximation; in fact, it is believed that the relative weighting suggested for shear and tensile values must be modified depending on the conditions of abrasion and the structure of yarn and fabric - which in turn determine the relative importance of the micro and macro snagging.⁽¹⁷⁷⁾ For finer abrasives more weight must be given to the shear component and conversely tensile behavior assumes greater importance in more severe wear. The repeated impacts of abrasion will of course call for more complex combinations of properties such as are listed on Page 32,⁽⁷²⁾ but it is important to add that multidirectional properties must be considered in instances where multidirectional stresses are to be expected. Needless to say, surface abrasion represents the latter condition. Bursting tests of film material represent multidirectional strain and suggest a method of studying the complex behavior of the high polymers when subjected to two directional stresses.^(63,64,165,190)

Finally, modification of the directional properties of a given fiber through stretching or mechanically conditioning before or during⁽¹³²⁾ its use or test must be considered. In the latter instance it becomes evident that an entirely different material, mechanically speaking, is being tested than was measured in the original state. The higher orientations which result from repeated stresses will affect the nature of fibrillar breakdown due to subsequent mechanical action.^(65,212) This has been clearly demonstrated in the crushing of nitric acid treated viscose fibers of varying degrees of orientation (through stretching). Here⁽²⁰⁵⁾ it was noted that the unorientated material broke into nonuniform segments which were cleaved to approximately the same extent in all directions. In the case of the oriented fibers disintegration took place longitudinally and uniform spirally located fibrils became evident. The degree of spirality depended upon the orientation and in some cases approached the angles of the fibrils evident in mechanically damaged cotton fibers.⁽¹¹⁵⁾

It has been shown that direction of abrasion as related to molecular, fibrillar, fiber and yarn geometry has a marked effect on the wear resistance of textile structures. The surface curvatures of fiber and yarn determine the relative shear and tensile vectors which are brought to play during directional abrasive action. The importance of considering the directional properties of fibers subjected to the multidirectional stresses of abrasive attrition is stressed and it is concluded that the relative affect of shear and tensile behavior will depend upon the nature of wear, whether of a micro-frictional or a macro-snagging pattern. Finally, it is concluded that optimum design of wear-resistant fabrics can be achieved by protecting the stress-bearing yarns and by orienting the components of the exposed yarns with respect to the nature and direction of abrasion so as to reduce their rate of attrition.

COMPLIANCY

As Related to Compressional Properties

The influence of backing materials in abrasion testing is well known although little is reported in the literature since most investigators standardize on the type of backing used in a given test. The various degrees of backing softness on a man's body will have effect on the relative wear of different portions of his garment. This factor is believed to play an important role in the variation in wear scores recorded in combat course tests of Army clothing, although it is not assumed for a moment that the major factor does not coexist in the wearing habit of the individual, that is, what portions of his body he brings into contact with the different abrasive

elements which occur during traversal of the course. Soft backing, extra padding thickness, or napping of fabrics in test will add to the compressive give and therefore to the ability to escape damage through surface abrasion. (66,84,96,171)

Finally, it is concluded that the compressive behavior of the surface structure itself bears on its wear performance and it may be expected that a low compressive modulus and high rate of recovery will enhance abrasion resistance, reducing the normal pressures at local projections.

As Related to Fabric Tightness

Reduction in the extent of fiber plucking during wear, by closer weaves or high twist, should not be carried out at the expense of local rigidity at the fabric surface. There is sufficient evidence to demonstrate that tightly woven, knuckled fabrics possess low wear resistance. (88,139,216) This, in fact, is caused by the inability of the surface fiber to move in translation to avoid the passage of the abradant particle; as a result, stresses are set up which exceed the shear tenacity at the localized point of contact, or the tensile tenacity in cases of macrosnagging. (171) The motility required to alleviate surface stresses on individual fibers can be achieved by rotation of the yarn or translational movement of the yarn within the fabric structure.

Yarn rotation will depend upon twist, T , and fiber tensile modulus, M , which in turn affect torsional rigidity, g , where $g = fTM$. With a given surface force, F , and yarn radius, r , the rotational moment, M , is the product of $F \times r$. It is seen that rotation of the yarn will take place until the localized shear stress or the tensile stress exceeds the fiber limit. Since

$$M = \frac{a G I}{j} = F \times r = \frac{a f(TM)I}{j} ,$$

where a is the angle in radians through which the yarn rotates at the point of thread-abrasive contact, I the polar moment of inertia of the thread, and j the distance from the end of the float to the thread-abrasive contact point,

it may be expected that if rotation, a , when F is the maximum that the fiber will bear, is not sufficient, then whole or sectional rupture of the fiber will occur.

From the above expression it is seen that excess shearing stresses and high transmittal of tensile stresses may be avoided by increasing the yarn radius, r , the float length, $2j$, and decreasing the twist, T , and the tensile modulus, M , of the fibers.

In repeated impacts of the abradant it is important that the fiber and yarn return to their original position before approach of the second particle. If struck while in the rotated position, the increased T will cause an increased F to be set up before the necessary rotation, α , for clearance of the abradant particle can be reached. Under such conditions higher shear and tensile stresses will be transmitted to the surface fibers leading to their early rupture.

It follows that the ability of the yarn to recover its original position before the approach of subsequent abradant particles will significantly affect its wear resistance. This recoverability is related to:

- (1) The inherent immediate elastic properties⁽⁷²⁾ of the fibers.
- (2) The twist of the yarn.
- (3) The distribution of sharp particles on the surface of the abrasive.
- (4) The relative velocity between abradant and specimen.
- (5) The path of the abradant across the specimen (extent of rest periods).^(45,155)

In field tests the material is often allowed to recover after abrasive treatments and thus heat of friction is disposed of and primary creep recovered so that yarn and fiber assume a position near to their original state. In laboratory tests, however there is no allowance for the time factor and relaxation between cycles^(52,175) and materials which cannot recover in time for repeated abrasive runs tend to have low abrasion resistance. Under modified conditions of abrasion it is likely that rankings may be easily reversed as the influence of yarn compliance is weighted differently.

The work which is expended on a fabric is thus seen to be divided into reversible and destructive portions. That portion which results in rupture of the specimen or its permanent set will of course contribute to wear damage. The smaller the particles removed with time or the greater the free surface of dislodged particles, the greater the energy needed from the frictional or abrasive forces. A practical limit has been noted for the worn particles which sets the amount of frictional energy that has been spent in destruction. It has been computed in one case⁽²⁰⁹⁾ that removal of the abraded solid in atomic particles would require less than 2 per cent of the

frictional energy utilized in the test. Actually the large particles abraded give evidence of even less of the frictional energy being used towards destruction of the solid.

The other portion of frictional energy which goes into displacement of yarn or fabric or straining the fibers in the elastic range, is converted to heat upon free recovery of the structure and its elements. This phenomenon is somewhat similar to the rolling wear of tires(211) in which a point of the tread comes in contact with the road, slipping until the normal pressure rises to a value where the friction force exceeds the resistant stress of the rubber. At this point the rubber will flow and store energy. As the point leaves the road, the stored energy will cause slippage and surface work or abrasion.

The point stressed in these examples is that the percentage of friction energy which goes into abrasive destruction is dependent on the nature of the surface and the mechanical properties of the material being rubbed.

Fabric compliance will depend upon the threads per inch and the type of weave. Geometric studies have shown that the number of picks which may be woven in a fabric is limited by the number of warp ends per inch. The limiting construction of picks for a given sley, or vice versa, is known as the jammed condition.(125,126) The quantitative expression of tightness as a ratio of actual picks (or ends) per inch to the maximum number per inch for a given cover factor, K, in the opposite direction is quite useful in fabric development. It will be recalled that the cover factor,

$$K = \frac{\text{Threads per inch}}{\sqrt{\text{yarn count cotton system}}}$$

It has been shown that for plain weaves(126)

$$\frac{28}{(1 + \beta) \sin \theta_2} = K_1$$

$$\frac{28\beta}{(1 + \beta) \sin \theta_1} = K_2$$

$$\cos \theta_1 + \cos \theta_2 = 1$$

for the jammed condition, where $\beta = \sqrt{\frac{N_1}{N_2}}$, θ is the angle of inclina-

tion of the yarn angles in the crimp diagram (Figure 14), and subscripts 1 and 2 refer to warp and filling respectively. By selecting increasing values of θ the relationship between K_1 and K_2 for different values of β can be obtained. These relationships have been plotted and used extensively in the Quartermaster laboratories.

In considering weaves other than the plain weave, one must correct for differences in intersections between fabrics. This can be done by adjusting the measured cover factors for each weave and using the corrected values in the above expression. The formula for cover factor adjustment is:

$$K_2^1 = \frac{28 K_2}{28M_2 - K_2(M_2-1)f_2}$$

$$K_2^1 = \frac{28 K_2}{28M_1 - K_2(M_2-1)f_2}$$

where K is the measured cover factor, K^1 the corrected cover factor, M weave factor computed by dividing the number of yarns in a repeat by the number of crossovers of the opposite set of yarns per repeat, and f the relative degree of flattening of the yarns expressed as a ratio of major axis of flattened yarn to diameter of round yarn.

Using the above measures it is seen that fabrics with high M values can pack considerably more yarn per unit area without increasing tightness with a corresponding reduction in abrasion resistance and tear resistance. Meanwhile, the increased bearing surface of the higher textured fabrics results in reduced abrasive pressure per crown or float and less abrasive damage. As a logical conclusion it is noted that the sateen construction shown to be most wear resistant in Army field tests has a maximum M of 2.5. On the other hand, tests of these same constructions show up poorly⁽¹⁸⁰⁾ under laboratory conditions where the compliance and recoverability fostered by a high M are negated by fine abradants and high speeds. Anomalies in abrasion testing will continue. It is therefore incumbent upon the individual investigator to see that the conditions of abrasion testing⁽⁴⁰⁾ are related to service circumstance and that laboratory testing is confirmed wherever possible by service trials.⁽⁴⁷⁾ An important approach to the problem is the study of worn garments from varied groups of consumers. Here will be found valuable evidence of the nature of service wear and clues as to the type of laboratory tests best suited to predict the type of service performance for the particular instance. Here, too, will be observed weak spots in fabric structure, finish, manufacturing technique, seam and stitch construction, thread quality,

and garment design. Any or all of these features have been found in Army surveys to lead to salvaging of military garments. Such surveys(54,136,137,144) conducted during and after the war serve as base points for improvement of Army fabrics and garments.

Development of improved laboratory abrasion equipment has been a successful part of this program(152,177) and while confidence is had in results obtained to date, careful study of the variables indicated above lead Quartermaster investigators to exercise extreme caution in attempting to predict performance of new fibers, fabric constructions, or finishes under conditions of service which have not been thoroughly studied for standard textile materials.

In summary, it may be said that the abrasion resistance of textile structures may be enhanced by reduction of stress concentration at local points. An efficient method of achieving the degree of compliance required is through fabric construction. Long floats are, within limits, a standard method of increasing yarn compliance. But recognition must be had of the complex geometric interactions of yarn size, thread frequency, and weave pattern which govern fabric tightness.

CONCLUSIONS

1. Friction and abrasion are but related portions of a complete spectrum of mechanical surface phenomenon resulting from relative motion between solids. While friction resistance and wear damage are coincidental in surface motion the relationship is not a direct one, nor does all frictional energy contribute to wear.

2. Frictional resistance and accompanying wear is a function of the conditions of rubbing between surfaces. Pressure, tension, speed of rubbing, temperature and moisture conditions are all significant factors to be considered in evaluating the results of service and laboratory tests of wear resistance. It follows that conditions of laboratory evaluations must resemble those incurred in field service if valid product improvement is to be realized.

3. Friction and wear data must always be critically reviewed in the light of (a) the conditions of lubrication which exist between rubbing surfaces, and (b) the changes in surface property of both bodies as a result of the rubbing action.

4. The wear of elastic solids is dependent on their hardness, surface roughness and shear resistance. Contrasted to this, textile fabrics depend for their abrasion resistance on:

- (a) Geometric area of contact under uniform abrasive pressure.
- (b) Protection of stress-bearing members from surface attrition.
- (c) Orientation of micro and macro components of surface-exposed elements so as to reduce localized directional wear damage.
- (d) Translational yarn and indigenous fiber tensile compliance of a high order with rapid recovery, i.e., structure of optimum tightness and low tensile modulus with high percentage of elastic recovery.
- (e) High shear strength under conditions of axial tensile loading.

5. Future work in the problem of wear resistance of textiles should include:

- (a) Classification of the conditions of abrasive surface and speed, pressure, and direction of rubbing in service of the most commonly used apparel fabrics.

- (b) Establishment of corresponding laboratory test conditions with full cognizance of the numerous variables affecting surface wear.
- (c) Establishment of the condition of fabric in which maximum fabric wear is incurred in service, i.e., with respect to laundering, dry cleaning and mechanical conditioning.
- (d) Development of uniform and constant abrasive surfaces for laboratory tests corresponding to the various classifications of wear met in service.
- (e) Development and demonstration of the adequacy of nondestructive methods to evaluate wear damage of textile structures.
- (f) Study of the multidirectional stress behavior of high polymers with repeated applications of load with a view towards fitting the balance between fiber properties with the tensile and shear requirements of special abrasive conditions.
- (g) Critical analysis of service-worn apparel to ascertain the mechanisms of mechanical failure and thus separate the effects of surface attrition dealt with here from those of excess tensile, burst, shear, or puncture stresses of normal service.

ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to the following individuals of the Quartermaster Corps whose contributions have made this report possible: Mr. Seaman J. Tanenhaus, formerly head of the Quartermaster wear-resistance project, and his assistant, Mrs. Mary Darby, who have secured much of the data used in this paper and whose reports have been freely quoted; Mr. Mario R. Pesce, who provided the photomicrographs and many of the other photographs used in this paper; Mr. Jack Salmon, who assisted in reproduction of the illustrative material; Mr. Gerald Winston and his assistant, Mr. John Medernach, who arranged and prepared the graphs and charts; Dr. Reinhold Stoll, who reviewed the entire paper and offered many helpful comments and suggestions; Mr. Norman E. Roberts, who carefully edited the paper, and his assistant, Mrs. Mary Keegan, who arranged the bibliography; The personnel of the Quartermaster Board; and finally Dr. S. J. Kennedy, whose continued interest in the wear-resistant phase of the Quartermaster textile program has been a source of encouragements and inspiration to the author.

BIBLIOGRAPHY

1. Adam, N.K., The Physics and Chemistry of Surfaces. Third Edition, London, Oxford University Press, p. 219 (1941).
2. Amontons, Memoires Academy Royal Science, 206 (1699); 96 (1704)
_____, Memoires de Mathematique et de Physique, 259 (1699).
3. Backer, S., Increasing Wear Life of Army Textiles Through Research. Quartermaster Conference on Research, National Academy of Sciences 25 Oct. 1945, New York: Textile Research Institute.
4. Ball, H.J., Problems Which Abrasion and Wear Testing Present. Textile Research J., 8, 134 (1938).
5. Ballou, J.W. and Silverman S., Sound Velocity Measurements. Textile Research J., 14, 282 (1944).
6. Bastow, S.H. and Bowden, F.P., On the Contact of Smooth Surfaces. Proc. Roy. Soc., London, A, 134, 404 (1931).
7. _____, Physical Properties of Surfaces. II. Viscous Flow of Liquids Films, The Range of Action of Surface Forces. Proc. Roy. Soc., London, A, 151, 220 (1935).
8. Beckwith, O.P., The Use of Army Service Testing Techniques and The Development and Interpretation of Laboratory Textile Tests. Quartermaster Conference on Research, National Academy of Sciences, 25 Oct. 1945, New York: Textile Research Institute.
9. Beeck, O., Physical Aspects of Boundary Lubrication. J. App. Phys., 12, 512 (1941).
10. _____, Givens, J.W., Smith, A.E., and Williams, E.C., On the Mechanism of Boundary Lubrication. Proc. of the Special Summer Conference on Friction and Surface Finish, Cambridge: Massachusetts Institute of Technology, p. 112 (1940).
11. Beilby, G., Aggregation and Flow of Solids, London: Macmillan (1921).
12. Bikerman, J.J., Surface Roughness and Sliding Friction. Revs. of Modern Phys., 16, 53 (1944).
13. Blok, H., Fundamental Mechanical Aspects of Boundary Friction Lubrication. S.A.E. Journal, 46, 54 (1940).

14. Boehringer, H., Staple Fiber Research, Comparative Tests on Wool Type Staple Fibers. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany during World War II. Heidelberg: Melliand Textilberichte, p. 334 (1949).
15. _____, Qualitative Criteria for Staple Rayon (I and II). Melliand Textilberichte, 22, 358, 409 (1941).
16. _____, and Schieber, W., Testing the Serviceability of Textile Fibers. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany during World War II. Heidelberg: Melliand Textilberichte, 245 (1949).
17. Bowden, F.P. and Bears, W.G., Physical Properties of Surfaces. I. Kinetic Friction. Trans. Roy. Soc., London, A, 234, 329 (1935).
18. _____ and Hughes, T.P., The Friction of Clean Metals and the Influence of Adsorbed Gases. The Temperature Coefficient of Friction. Proc. Roy. Soc., London, A, 172, 263 (1939).
19. _____, Physical Properties of Surfaces. IV. Polishing Surface Flow and the Formation of the Beilby Layer. Proc. Roy. Soc., London, A, 160, 575 (1937).
20. _____, Friction of Clean Metals and the Influence of Surface Films. Nature, 142, 1039 (1938).
21. _____, The Mechanism of Sliding on Ice and Snow. Proc. Roy. Soc., London, A, 172, 280 (1939).
22. _____ and Leben, L., The Nature of Sliding and the Analysis of Friction. Proc. Roy. Soc., London, A, 169, 371 (1938).
23. _____, and Tabor, D., The Sliding of Materials, Frictional, Fluctuations and Vibrations of Moving Parts. The Engineer, 168, 214 (1939).
24. _____, Moore, A.J.W., and Tabor, D., Ploughing and Adhesion of Sliding Metals. J. App. Phys., 14, 80 (1943).
25. _____ and Ridler, K.E.W., Physical Properties of Surfaces. III. The Surface Temperature of Sliding Metals, The Temperature of Lubricated Surfaces. Proc. Roy. Soc., London, A, 154, 640 (1936).
26. _____ and Tabor, D., Contact of Colliding Surfaces. Melbourne: Council for Scientific and Industrial Research (1942).

27. _____, The Area of Contact Between Stationary and Between Moving Surfaces. Proc. Roy. Soc., London, A, 169, 391 (1938).
28. Brackett, W.R., Floyd, E.V., and Dennen, A.C., New Abrasion Machine Controls Temperature, Humidity, Pressure, Tension, and Rate of Rubbing. Textile World, 74, 65 (1928).
29. Breazeale, F., Apparatus for Determining Coefficient of Friction of Running Yarn. Textile Research J., 17, 27 (1947).
30. Bright, T.B., The Microscopic Examination of Damaged Cotton Hairs by The Congo Red Test and the Swelling Test of Fleming and Thaysen. J. Textile Inst., 17, T396 (1926).
31. Browning, W., Notes on Electrical Conductivity. J. Inst. Elec. Engrs., 37, 372 (1906).
32. Buckle, H. and Pollitt, J., An Instrument for Measuring the Coefficient of Yarns Against Other Materials. J. Textile Inst., 39, T199 (1948).
33. Burwell, J.T., Kaye, J., and Van Nymegen, D.W., Effect on the Metal Removed from a Journal During the Running-In Process. Proc. of the Special Summer Conferences on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology, p. 209 (1940).
34. _____ and Strong, C.D., The Incremental Friction Coefficient, A non-Hydrodynamic Component of Boundary Lubrication. J. App. Phys., 20, 79 (1949).
35. Campbell, W.E., Remarks on "Automatic Machines for Investigating the Boundary Phenomenon in Sleeve Bearing. Proc. of the Special Summer Conferences on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology, (1940).
36. Carlene, P.W., Measurement of the Bending Modulus of Monofils. J. Textile Inst., 38, T38 (1947).
37. Cassie, A.B.D., Physical Properties of Fibres and Textiles Performances. J. Textile Inst., 37, P154 (1946).
38. Clapham, H.F., Washable Woolens for the Army, Quartermaster Conference on Research, National Academy of Sciences, 25 Oct. 1945. New York: Textile Research Institute.
39. Clegg, G.G., Examination of Damaged Cotton by the Congo Red Test; Further Developments and Applications. J. Textile Inst., 31, T49 (1940).

40. Collins, G.E., Construction of Fabrics for Specific Purposes, J. Textile Inst., 37, P392 (1946).
41. Connor, K.W. and Martz, L.S., Functionalism in Surface Finish. Proc. of Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
42. Coulomb, Memoires Academy Royal Science, 161 (1785); Theorie des Machines Simples (Paris 1809).
43. Crawshaw, H., Morton, W.E., and Brown, K.C., Experiments on Fabric Wear Testing. J. Textile Inst., 22, T64 (1931).
44. Davis, W. and Buckley, G.H., Abrasion Testing of Knitted Textiles, J. Textile Inst., 25, T133 (1934).
45. Dawson, T.R., Abrasion and Wear Testing of Textile Fabrics, J. of Rubber Research, 15, 65 (1946).
46. Dayton, R.W., Mechanisms of Wear: Their Relation to Laboratory Testing and Service. Proc. of the Special Summer Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
47. Dean, F.R., Recent Advances in Abrasion Testing of Textiles. J. Textile Inst., 37, P380 (1946).
48. Dickson, J.B., Development Report. U.S. Rubber Company, 25 April 1949. (Unpublished) (Private Communication).
49. Ditton, E. N., Service Wearing Tests. Rayon Textile Monthly, 29, 69 (June 1948).
50. Dokos, S.J., Sliding Friction Under Extreme Pressures. J. App. Mechanics, 13, A148 (1946).
51. Dreby, E.C., A Friction Meter for Determining the Coefficient of Kinetic Friction of Fabrics. J. of Research of the Natl. Bureau of Standards, 31, RP 1562, 237 (Oct. 1943).
52. Dunkerley, J.R., Wear Resistance of Fibers. Textile Industries, 112, 110 (Dec. 1948).
53. Edelman, N.B., The Coefficient of Friction of Herringbone Twill Rubbing Against Itself. Textile Research Laboratory, Philadelphia Quartermaster Depot, 5 Jan. 1946. (Unpublished).

54. Edwards, J., Wear Resistance of Textiles, Survey of Field Abrasion. Bi-Monthly Report, 1 Jan. 1947, to the Research Laboratory, Philadelphia Quartermaster Depot. (Unpublished).
55. Edwards, W.F., Wearing Tests on Textile Fabrics. Textile World, 69, 3817 (1926).
56. Ernst, H. and Martellotti, M., Metal Cutting. Mechanical Engineer, 57, 487 (1935).
57. _____ and Merchant, M.E., Surface Friction of Clean Metals - A Basic Factor in the Metal Cutting Process. Proc. of the Special Summer Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
58. _____, Chip Formation, Friction, and High Quality Machined Surfaces. Symposium on the Surface Treatment of Metals. 22nd Annual Convention of ASM, Cleveland, O., Preprint 21-25 Oct., 1940, 299 (1941).
59. Fachausschuss fuer Zellwolle, Typenerzeugung und Preisbildung (RCF), Specifications for Testing Serviceability of Wool Type Staple Rayon. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany during World War II. Heidelberg: Melliland Textilberichte, p. 193 (1949).
60. Federoff, N.S., Russian Study of the Wearing Qualities of Fabrics. Textilnaya Promyshlennost (Textile Industry), 7, 41 (1948).
61. Finch, G.I. and Quarrell, A.G., The Beilby Layer. Nature, 137, 516 (1936).
(_____, Letter to the Editor, Beilby Layer, Nature, 138, 1010 (1936/)).
62. Finlayson, D., The Shear Strength of Filaments and Fibers. J. Textile Inst., 38, T50 (1947).
63. Flint, C.F. and Naunton, W.J.S., Physical Testing of Latex Films. I.R.I., Trans. 12, 367 (1937).
64. Forrester, P.G., Kinetic Friction In or Near the Boundary Region. Proc. Roy. Soc., London, A, 187, 439 (1946).
65. Franz, E., Morphological Structure and Quality of Textile Fibers. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melliland Textilberichte, p. 347 (1949).

66. Freedman, E., Factors Influencing Tensile Strength and Wear Resistance of Blanket Materials. Papers of Am. Assoc. of Textile Technologists, p. 85, December 1945 to March 1946.
67. Gekker, D.A., Russian Study of the Durability of Fabrics in Connection with Their Laundering. Textilnaya Promyshlennost (Textile Industry) 7, 43 (July 1948).
68. Gemant, A., Frictional Phenomena. J. App. Phys., 12, 530, 626, 718, 724, 827 (1941); 13, 22, 90, 210, 290, 355, 688, 718 (1942); 14, 456, 464 (1943).
69. Gralen, N. and Olofsson, B., Measurement of Friction Between Single Fibers. Textile Research J., 17, 488 (1947).
70. Hamburger, W.J., Mechanics of Elastic Performance of Textile Materials, I. Development of Elastic Performance Coefficient in Tension. Textile Research J., 18, 102 (1948).
71. _____, Mechanics of Elastic Performance of Textile Materials, II. The Application of Sonic Techniques to the Investigation of the Effect of Visco-Elastic Behavior upon Stress-Strain Relationships in Certain High Polymers. Textile Research J., 18, 705 (1948).
72. _____, Mechanics of Abrasion of Textile Materials. Textile Research J., 15, 169 (1945).
73. _____ and Lee, H., A Study of Lining Fabric Abrasion. Rayon Textile Monthly, 26, 341, 385 (1945).
74. Hardy, W.B., Collected Scientific Papers. London: Cambridge University Press (1936).
75. Harvey, E.H., Wyzenbeek Precision Wear-Tester. Am. Dyestuff Rep., 21, 177 (1932).
76. Haven, G.B., Abrasion Testing Machine. Textile World, 76, 2654, (1929).
77. Hays, M.B., Physical Properties of 26 Work Garment Fabrics. Rayon Textile Monthly, 25, 28 (1944).
78. Henniker, J.C. and McBain, J.W., The Depth of the Surface Zone of a Liquid. Stanford Research Institute, Stanford, California, Report No. 5, Properties of Surfaces N6orI-154-T.O.II, 31 March 1948. (Unpublished).

79. Hicks, E.M. and Scroggie, A.G., Taber Yarn-Sheet Abrasion Test. Textile Research J., 18, 416 (1948).
80. Hire, deLaP., Histoire de l'Academie, 104 (1699).
81. Hock, C.W., An Electron-Microscopical Examination of Rayon. Textile Research J., 18, 366 (1948).
82. _____ and McMurdie, H.F., Structure of the Wool Fiber as Revealed by the Electron Microscope. J. of Research of the Natl. Bur. of Standards, 31, RP 1561, 229 (Oct. 1943).
83. Hunter, M.C., Static and Clinging Friction of Pivot Bearings. Inst. of Mech. Engrs., Proc. 151, 274 (1944).
84. Jaumann, A., Upholstery Fabrics: Testing. Kunstseide, 21, 9, (1939).
85. Jones, H., The Temperature Sensitivity of the System Plasticizer-Polymer. J. Soc. Chem. Ind., 67, 415 (1948).
86. Karalitz, G.B., Boundary Lubrication. Proceedings of the Special Summer Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
87. Kaswell, E.R., Wear Resistance of Apparel Textiles, I. Tests of Military Fabrics on Quartermaster Combat Course. Textile Research J., 16, 413 (1946).
88. _____, Wear Resistance of Apparel Textiles, II. Laboratory Evaluation of Military Fabrics and Correlation with Combat Course Tests. Textile Research J., 16, 502 (1946).
89. Kennedy, S.J., Problems for Future Quartermaster Textile Research. Quartermaster Conference on Research, National Academy of Sciences, 25 Oct. 1945. New York: Textile Research Institute.
90. Kock, P.A., Satlow, G., and Bobeth, W., Examination of the Wear Resistance of Cotton and Staple Fiber Fabrics with Apparatus. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melland Textilberichte, p. 9 (1949).
91. Larose, P., A New Form of Abrasion Tester. Can. J. of Research, 18, A, 161 (1940).
92. Leaderman, H., Elastic and Creep Properties of Filamentous Materials and Other High Polymers. Washington: Textile Foundation, 278 pp. (1943).

93. Leites, L.G., Russian New-Structure Fabrics for Bed Linen and Underclothes. *Textilnaya Promyshlennost (Textile Industry)* 9, 21 (Sept. 1948).
94. _____ and Margolin, I.S., New Russian Device for the Evaluation of the Surface Structures of Fabrics in Connection with Their Examination for Wearing and Sanitary Hygienic Properties, *Textilnaya Promyshlennost (Textile Industry)* 6, 26 (June 1948).
95. Lester, J.H., Abrasives for Wear Testing. *J. Textile Inst.*, 28, P209 (1937).
96. _____, Mather Lecture, 1935, Avenues of Progress in the Textile Industry. *J. Textile Inst.*, 26, P95 (1935).
97. Lindberg, J., Measurement of Friction Between Single Fibers. III. Influence of Different Treatments on the Frictional Properties of Wool Fibers. *Textile Research J.*, 18, 470 (1948).
98. _____ and Gralen, N., Measurement of Friction Between Single Fibers. II. The Frictional Properties of Wool Fibers Measured by the Fiber Twist Method. *Textile Research J.*, 18, 287 (1948).
99. Mahannah, E.A. and Bailey, H.P., Apparatus for Testing Material. U.S. Patent 2,189,589, 6 Feb. 1940.
100. Mann, J.C., The Serviceability of Fabrics for Clothing: The Testing of Fabrics for Resistance to Abrasion. *J. Textile Inst.*, 28, P220 (1937).
101. _____ and Peirce, F.T., The Time Factor in Hair Testing. *J. Textile Inst.*, 17, T82 (1926).
102. Martin, A.J.P., Observations on the Theory of Felting. *J. of the Soc. of Dyers and Colourists*, 60, 325 (1944).
103. Matthew, J.A., A Cloth Wear Testing Machine. *J. Textile Inst.*, 21, T546 (1930).
104. _____, Comparison of Some Fabric Test Methods. *J. Textile Inst.*, 22, T497 (1931).
105. Matthew's Textile Fibers, 5th Edition. New York: John Wiley & Sons, Inc. (1947).

106. Mendrzyk, H., Sommer, H., and Viertel, O., Methods of Improving Serviceability of Military Cloth. Development in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melliand Textilberichte, 130 (1949).
107. Mercer, E.H. and Makinson, K.R., The Frictional Properties of Wool and Other Textile Fibers. J. Textile Inst., 38, T227 (1947).
108. Merchant, M.E., Letter to the Editor, J. App. Phys., 11, 230 (1940).
109. Mercier, A.A., Coefficient of Friction of Fabrics, J. of Research of the Natl. Bur. of Standards, 5, 243 (1930).
110. Meredith, R., Tensile Behavior of Raw Cotton and Other Textile Fibres. J. Textile Inst., 36, T107 (1945).
111. _____, The Determination of Tensile Properties and Torsional Rigidity of Fibres. J. Textile Inst., 38, T15 (1947).
112. _____, Elastic Properties of Textile Fibres. J. Textile Inst., 37, P469 (1946).
113. _____ and Peirce, F.T., A Cumulative Extension Test for Plasticity in Textile Fibres. J. Textile Inst., 39, T159 (1948).
114. Midgley, E. and Peirce, F.T., Tensile Tests for Cotton Yarns.
i. A Survey of Current Tests. J. Textile Inst., T305;
iii. The Rate of Loading. Ibid., T330 (1926).
115. _____, Tensile Tests for Cotton Yarns.
The Rate of Loading (Addendum). Ibid., T661. (1926).
116. Morgan, F., Muskat, M., and Reed, D.W., Studies in Lubrication. Friction Phenomena and Stick-Slip Process. J. App. Phys., 12, 743 (1941).
117. Morrow, J.A., The Frictional Properties of Cotton Materials. J. Textile Inst., 22, T425 (1931).
118. Morton, W.E., The Designing of Fabrics to Meet Consumers Requirements. J. Textile Inst., 39, P187 (1948).
119. _____ and Permyner, F., The Measurement of Torsional Relaxation in Textile Fibres. J. Textile Inst., 38, T54 (1947).
120. _____ and Turner, A.J., The Influence of the Degree of Twist in Yarns on the Results of Yarn Mercerization and on the Properties of Plain Fabrics Made from Grey or Mercerized Cotton Yarns. Part II - The Results of Various Strength Tests on the Fabrics. J. Textile Inst., 19, T189 (1928).

121. Muhlethaler Kurt, Electron Micrographs of Plant Fibers. Biochim. et Biophys., Acta, 3, 15 (1949).
122. Myers, W., The Examination and Testing of Cloth. National Association of Cotton Manufacturers, Trans., 91, 100 (1912). The Effect of Structure on the Strength and Wearing Qualities of Cloth. Ibid., 97, 121 (1915).
123. Opatowski, I., A Theory of Brakes, An Example of a Theoretical Study of Wear. J Franklin Inst., 234, 239 (1942).
124. Owen, A.E. and Locke, J., The Measurement of the Resistance of Yarns to Abrasion. J. Textile Inst., 17, T567 (1926).
125. Peirce, F.T., Geometrical Principles Applicable to the Design of Functional Fabrics. Textile Research J., 17, 123 (1947).
126. _____, The Geometry of Cloth Structure. J. Textile Inst., 28, T45 (1937).
127. _____, The Rigidity of Cotton Hairs. J. Textile Inst., 14, T1 (1923).
128. _____, The Serviceability of Fabrics in Regard to Wear: Testing Fabrics to Foretell Serviceability. J. Textile Inst., 28, P181 (1937).
129. _____, The Plasticity of Cotton and Other Materials. J. Textile Inst., 14, T390 (1923).
130. Pesce, M.R., Surface Sectioning of Textile Materials. Memo Report, Microscopy Unit, Quartermaster General Laboratories, Philadelphia Quartermaster Depot, 31 Jan. 1949 (Unpublished)
131. Petrie, T.C., The Serviceability of Fabrics in Regard to Wear. J. Textile Inst., 28, P206 (1937).
132. Platt, M. and Hamburger, W.J., A Study of the Effects of Form Factors on the Translation of the Inherent Properties of Textile Fibers in the Structures, Quartermaster Corps Research Contract Reports, Supplemental Report, Section XI, 25 August 1947 (Unpublished).
133. Posdnjakov, B.P., Cotton Fabrics: Wearing Tests. Legkaja Prom., 15, No. 5, 151 (1936).
134. Preston, J.M., Fibre Science. Manchester: The Textile Institute, pp. 206, 207 (1949).

135. Quartermaster Board Report of Test of Wear Resistance of Apparel Textiles. Project T510, Camp Lee, Va., 8 Nov. 1945 (Unpublished).
136. Quartermaster Board, Project S163, Salvage in Western Pacific. Includes Clothing, Footgear, Equipment and Tentage, Conducted in the Philippine Islands and Japan from 16 Nov. 1945 through 22 Jan. 1946 (dated 15 April 1946).
137. Quartermaster Board, Clothing Failure Study of M1943 Combat Uniform, QMB-S-169, I, II, III, Camp Lee, Va., 4 June 1947 (Unpublished).
138. Quartermaster Board Letter Report, Wear Resistance of Fabrics, Effect of Nylon-Cotton Blends. Camp Lee, Va., 23 Oct. 1947 (Unpublished).
139. Quartermaster Board Letter Report, Wear Resistance of Fabrics, Effect of Weave. Camp Lee, Va., 20 Nov. 1947 (Unpublished).
140. Quartermaster Board Letter Report, Wear Resistance of Fabrics, Effect of Plant Finishing. Camp Lee, Va., 4 Dec. 1947 (Unpublished).
141. Quartermaster Board Letter Report, Wear Resistance of Fabrics, Effect of Texture. Camp Lee, Va., 1 March 1948 (Unpublished).
142. Quartermaster Board Letter Report, Wear Resistance of Fabrics, Effect of Yarn Count. Camp Lee, Va., 26 July 1948 (Unpublished).
143. Quartermaster Board, Report of Test of Glove, Insert, Wool, QMB-T-4804-665. Camp Lee, Va., 31 Jan. 1949 (Unpublished).
144. Quartermaster Board, Project S169, Handbook for Study Team, Clothing Failure Study M-1943 Combat Uniform, 28 May 1946 (Unpublished).
145. Reichsvereinigung Chemische Fasern (RCF). Testing Serviceability of Cotton Type Staple Rayon. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melland Textilberichte, 159 (1949).
146. Rennie, G., Experiments on the Frictional Abrasion of the Surfaces of Solids. Phil. Trans. Royal Society of London, 19, 169 (1829).
147. Rosenzweig, A., Relative Durability of Textile Fabrics. Textile Mfr., 58, 212 (1932).

148. Roth, F.L., Driscoll, R.L., and Holt, W.L., Frictional Properties of Rubber, J. of Research of the Natl. Bur. of Standards, 28, RP 1463, 439 (1942).
149. Sakmann, B.W., and Burwell, J.T., Mechanism of Friction. J. Aeronaut. Sci., 11, 381 (1944).
150. _____ and Irvine, J.W., Measurement of the Adhesion Component in Friction by Means of Radioactive Indicators. J. App. Phys., 15, 459 (1944).
151. Saxl, E.J., Determination of Wearing Qualities by Air Flow Measurements. Am. Dyestuff Rep., 29, 637 (1940).
152. Schiefer, H.F., Final Report on Wear Resistance of Textiles to the Office of the Quartermaster General. Natl. Bur. of Standards, 15 Dec. 1948 (Unpublished).
153. _____, Performance Tests on Fifteen Serge Fabrics for Military Trousers. Report VII - 2/72, Natl. Bur. of Standards, 15 June 1945 (Unpublished).
154. _____, Fourt, L., and Kropf, R.T., Textile Testing in Germany. II Serviceability Evaluation of Textiles. Textile Research J., 18, 18; III Testing Flexural and Compression Properties. Ibid., 89 (1948).
155. Schniewind, H.Z., Fabric Abrasion Tester. Instruments, 3, 596 (1930).
156. Schnurmann, R., Amontons Law "Traces" of Frictional Contact and Experiment of Adhesion. J. App. Phys., 13, 235 (1942).
157. Schwartz, C.M., Austin, A.E., and Weber, P.M., A Positive Replica Technique for Electron Microscopy. J. App. Phys., 20, 202 (1949).
158. Schwarz, E.R., Machine for Determining the Resistance of Fabrics to External Abrasion. Textile World, 72, 739 (1927).
159. Shaw, P.E., Experiments on Tribo-Electricity. I The Tribo-Electric Series. Proc. Roy. Soc., London, A, 94, 16 (1917).
160. _____ and Hanstock, R.F., Tribo-Electricity and Friction. V On Surface Strain and Relaxation of Like Solids. Proc. Roy. Soc., London, A, 128, 474 (1930).
161. _____, Tribo-Electricity and Friction. VI On Surface Strain and Relaxation for Unlike Solids. Proc. Roy. Soc., London, A, 128, 480 (1930).

162. _____ and Jex, C.S., Tribo-Electricity and Friction. II Glass and Solid Elements, Proc. Roy. Soc., London, A, 118, 97 (1928).
163. _____, Tribo-Electricity and Friction. III Solid Elements and Textiles. Proc. Roy. Soc., London, A, 118, 108 (1928).
164. _____, Tribo-Electricity and Friction. Proc. Roy. Soc., London, A, 111, 339 (1926).
165. Sheppard, J.R. and Clapson, W.J., Compression Stress Strain of Rubber. Ind. and Eng. Chem., 24, 782 (1932).
166. Simon, C.L., Abrasive Wear Tests on Garment Lining Fabrics. Report to Philadelphia Quartermaster Depot, Philadelphia, Pa., 10 March 1943 (Unpublished).
167. _____, Abrasion Tests on Lining Fabrics. Report to Textile Materials Engineering Laboratory, 5 Jan. 1949 (Unpublished).
168. _____, Wearing Qualities and Methods Used in Testing Synthetic Yarns. Textile World, 83, 576 (1933).
169. Skinkle, J.H., Serviceability, Wear Abrasion, Am. Dyestuff Rep., 27, 113 (1938).
170. Smith, H.D., Textile Fibers, An Engineering Approach to Their Properties and Utilization. ASTM, Edgar Marburg Lecture (1944).
171. Sommer, H., Testing Abrasion Resistance of Textiles. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melliand Textilberichte, 59 (1949).
172. _____ and Burgstaller, F., Determining Bursting Energy in the Bursting Pressure Test. Ibid., p. 56.
173. _____ and Geist, F., Principles of Testing the Bursting Strength of Fabrics. Ibid., p. 33.
174. Steinberger, R.L., Torque Relaxation and Torsional Energy in Crepe Yarn. Textile Research J., 7, 83 (1936-37).
175. Stewart, J.R., Measuring Wear Resistance of Man-Made Fibres. Canadian Textile Journal, 22, 41 (1948).

176. Stoll, R.G., New Knowledge and Instruments for Testing the Durability of Textiles. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany during World War II. Heidelberg: Melliand Textilberichte, 85 (1949).
177. _____, An Improved Multipurpose Abrasion Tester and Its Application for the Evaluation of the Wear Resistance of Textiles. Textile Research J. 19, 394 (1949).
178. _____, Systematic Quality Testing, The Basis for Improving the Serviceability of our Textiles. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melliand Textilberichte, 79 (1949).
179. Swerdlow, M. and Seeman, G.S., A Method for the Electron Microscopy of Wool. Textile Research J., 18, 536 (1948).
180. Tait, J.H., Abrasion Resistance of Rayon Linings. Rayon Textile Monthly, 26, 171 (1945).
181. Taleporovskaya, V.V., Russian Study of the Effect of Dyeing Cotton on its Technological Properties. Textilnaya Promyshlennost (Textile Industry) 5, 17 (May 1948).
182. Tanenhaus, S.J., The Median as a Typical Value for Walker Yarn Abrader Data. Textile Research J., 17, 281 (1947).
183. _____, Improvement of the Wear Resistance of Military Apparel Fabrics, Effect of Weave and Texture, Quartermaster Textile and Leather Research Laboratory Report No. 24. Philadelphia Quartermaster Depot, 20 May 1948 (Unpublished).
184. _____ and Winston, G., Report of the ASTM Task Group Studying the Wyzenbeek Precision Wear Test Meter. ASTM Bull., No. 154, 74 (1948).
185. Taylor, R.H. and Holt, W.L., Small Inertia-Type Machine for Testing Brake Lining. J. of Research of the Natl. Bur. of Standards, 24, RP 1297, 531 (1940).
186. Tepnin, V.I., The Methodology of the Determination of the Durability of Cotton Fabrics. Legkie Metal, 7, No. 3, 85 (1938). (Chem. Abstr. 34, 6085).
187. Thomson-Houston Co., Ltd., British Patent 543434 (1940).

188. Thomson, R.M.K. and Traill, D., The Bending Fracture of Fibres. J. Textile Inst., 38, T43 (1947).
189. Tomlinson, G.A., A Molecular Theory of Friction. Phil. Mag., Series 7, 7, 905 (1929).
190. Treloar, L.R.G., Strains in an Inflated Rubber Sheet and the Mechanisms of Bursting. I.R.I. Transactions, 19, 201 (1944).
191. Underwood, A.F., Some General Aspects of Rubbing Surfaces, Proc. of Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
192. U. S. Army Specification, 6-312, Cloth, Cotton, Poplin, 6.75 oz., O.D. #7, Wind Resistant, Water Repellent, 12 Jan. 1943. (Cancelled 21 Sept. 1945).
193. U. S. Federal Specification, Denim, Shrunk, CCC-D-181, 30 March 1944. (Formerly CCC-D-151a).
194. U. S. Joint Army-Navy Specification JAN C-154, Cloth, Cotton, Herringbone Twill. 30 Nov. 1944. (Formerly U. S. Army 6-261.)
195. U. S. Joint Army-Navy Specification JAN C-298, Cloth, Cotton, Uniform Twill. 27 Feb. 1946. (Formerly U. S. Army 6-201B.)
196. U. S. Joint Army-Navy Specification JAN C-484, Cloth, Cotton, Oxford, Wind Resistant, Water Repellent. 31 July 1947. (Formerly U. S. Army 444.)
197. U. S. Joint Army-Navy Specification JAN C-557, Cloth, Cotton, Sateen, 9.0 oz., Wind Resistant, Water Repellent. 5 Feb. 1948. (Formerly U. S. Army 6-337.)
198. U. S. Marine Corps Specification, Cloth, Cotton, Herringbone Twill, 1 Feb. 1940. Revised 11 March 1942, Amended 9 Feb. 1949.
199. Vogt, W.W., Analysis of a Typical Angle Abrasion Machine. Ind. and Eng. Chem., 20, 302 (1928).
200. Wagner, E., Influence of Different Finishes on the Serviceability of Staple Rayon Shirting. Developments in the Wear Resistance of Textiles and Related Papers Published in Germany During World War II. Heidelberg: Melland Textilberichte, 95 (1949).
201. Walker, A.C. and Olmstead, P.S., Textile Yarn Abrasion Test. Textile Research J., 15, 201 (1945).

202. Wallace, D.A., Preparation of Smooth Surfaces. Proc. Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
203. Way, Stewart, Description and Observation of Metal Surfaces. Proc. Conference on Friction and Surface Finish. Cambridge: Massachusetts Institute of Technology (1940).
204. Weirick, E.S., Textile Testing Laboratory. Am. Dyestuff Rep., 21, 154 (1932).
205. Welch, L.M., Roseveare, W.E., and Mark, H., Fibrillar Structure of Rayon Fibers. Ind. and Eng. Chem., 38, 580 (1946).
206. Weston, W.H., Tropical Deterioration of Textile Products. Quartermaster Conference on Research, National Academy of Sciences, 25 Oct. 1945. New York: Textile Research Institute.
207. White, W.L., Deterioration of Quartermaster Fabrics in the Tropics. Quartermaster Review, 26, No. 3, 16 (1946).
208. Whitehead, J.R., Metallic Friction and Surface Damage at Light Loads. Research, 2, 145 (1949).
209. Whittaker, E.J.W., Friction and Wear. Nature, 159, 541 (1947).
210. Williams, H.M., Testing of Cloth for Wear Resistant: Recent Developments in Machine Construction. Wool Record and Textile World, 34, 105 (1928).
211. Williams, I., Measurement of the Abrasion Resistance of Rubber. Ind. and Eng. Chem., 19, 674 (1927).
212. Williams, J.G., Textiles on Test. London: Chapman and Hall, Ltd. (1931).
213. _____, Minimum Wearing Strength of Textile Fabrics, Textile Mfr., 40, 58 (1932).
214. _____, The Wearing Qualities of Fabrics. J. Textile Institute, 39, P164 (1948).
215. Winston, G., Analysis of the Effect of Texture Upon Abrasion Resistance of 2/1 Twill as Evaluated on the Combat Course, Camp Lee, Va. Memorandum, Quartermaster Textile Materials Engineering Laboratory, Philadelphia Quartermaster Depot, 3 May 1948 (Unpublished).

216. _____, Analysis of the Effect of Weave Upon the Abrasion Resistance of Five Fabrics as Evaluated on the Combat Course, Camp Lee, Va. Memorandum, Quartermaster Textile Materials Engineering Laboratory, Philadelphia Quartermaster Depot, 12 Dec. 1947 (Unpublished).
217. _____, Analysis of the Effect of Nylon on the Abrasion Resistance of Fabrics as Evaluated on the Combat Course, Camp Lee, Va. Memorandum, Quartermaster Textile Materials Engineering Laboratory, Philadelphia Quartermaster Depot, 26 Sept. 1947 (Unpublished).
218. _____, Analysis of the Effect of Different Methods of Finishing Upon Abrasion Resistance of Herringbone Twill as Evaluated on the Combat Course, Camp Lee, Va. Memorandum, Quartermaster Textile Materials Engineering Laboratory, Philadelphia Quartermaster Depot, 30 April 1948 (Unpublished).
219. _____, Effect of Yarn Count Upon the Wear Resistance of 2/1 Twill as Evaluated on the Combat Course, Camp Lee, Va. Memorandum, Quartermaster Textile Materials Engineering Laboratory, Philadelphia Quartermaster Depot, 14 June 1948 (Unpublished).
220. Zawin, I.N.N.; Wear Resistance Measured in Laboratory and Shop. Machinist (Kremsmunster, Austria) 92, 696 (1948)

APPENDIX

TABLE I

Physical Properties of Standard Service Fabrics

<u>Construction</u>	<u>Army</u>		<u>Marine Corps</u>	<u>Navy</u>
	<u>Sateen</u>	<u>Std. HBT</u>	<u>HBT</u>	<u>Denim</u>
Weave	5 harness	HBT 2/1 12 ends right 12 ends left	HBT 3/1 16 ends right 16 ends left	2/1 Twill
Weight, oz./sq.yd.				
Experimental	10.2	8.9	9.4	10.0
Theoretical			9.3	9.9
Texture				
Ends/inch	84	76	104	70
Picks/inch	63	46	50	47
Yarn Number, singles cotton				
Warp	13	13	17	8.5
Filling	10	8	8.2	13.2
Cover Factor Kw	23.0	21	25.0	24.0
Kf	20.0	16	17.0	13.0
Yarn Crimp, Per Cent				
Warp	12.3	11.3	12.6	27.6
Filling	14.6	11.3	10.2	10.2
<u>Physical Properties</u>				
Breaking Strength, lb.				
Warp	154	140	130	160
Filling	136	146	134	70
Tearing Strength, lb.				
Elmendorf - Warp	10.9	5.9	8.2	10.0
" - Filling	12.0	7.5	9.4	4.5
Tongue - Warp	10.7	3.8	6.2	--*
" - Filling	7.7	4.9	7.4	3.0
Thickness, 0.001"	26.4	19.5	20.4	25.8
Stiffness, 0.001 lbs.				
Warp	3.1	3.8	3.7	13.0
Filling	3.6	3.6	4.2	5.4
Air Permeability				
ft ³ /min/ft ²	9.8	21.4	14.9	18.0
Wear Score, Revised				
(Camp Lee)	8.0	23.0		
Warp Yarn in the Left Twill - Z twist				
Warp Yarn in the Right Twill - S twist				

*Did not tear in warp. Tore across the filling.

APPENDIX

TABLE II

Laboratory Data - Camp Lee Series

	Group I - Nylon				Group II - Weave				Group IV - Texture					Group V - Yarn Count					Standard HBT
	23XN		50XN		HBT	HBT, M	PLAIN	OXFORD	SATEEN	84x55	84x45	78x50	72x55	72x45	10x8	10x12	16x8	16x12	
	111	114	117		100	103	104	107	112	24	28	31	34	38	15	17	54	56	
Fabric Number	111	114	117		100	103	104	107	112	24	28	31	34	38	15	17	54	56	
Texture, Warp	84.1	84.6	84.0		81.3	82.1	81.5	84.9	85.5	88.2	89.1	81.8	76.9	76.1	75.6	76.8	75.6	79.6	76
Filling	62.8	65.3	65.1		53.7	54.9	52.4	53.7	60.6	59.4	49.0	54.3	58.5	47.7	57.0	59.5	59.9	60.9	46
Weight, oz./sq.yd.	10.2	10.6	10.0		9.9	10.1	9.2	9.7	10.5	10.5	9.7	9.8	10.2	8.7	12.2	10.4	9.8	8.5	8.9
Breaking Load, lb. Strip, Warp	127	124	125		116	116	103	126	101	120	109	112	104	114	118	131	96	97	127
Filling	106	111	108		112	102	121	128	83	116	87	99	111	89	144	97	149	90	87
Grab, Warp	154	150	149		150	148	148	156	152	180	171	156	146	142	199	191	126	115	140
Filling	136	144	122		118	121	140	147	132	157	104	126	146	104	203	113	190	104	146
Elongation, Grab, %																			
Warp	22.3	24.7	23.8		30.5	31.4	27.2	27.3	25.2	32.2	31.5	34.9	27.0	25.2	32.2	37.3	29.7	26.3	17.7
Filling	24.8	26.5	26.9		20.8	22.6	18.2	23.5	27.4	19.7	18.1	21.4	24.4	20.0	22.5	20.1	24.4	25.3	21.7
Tearing Strength, lb.																			
Tongue, Warp	10.7	10.9	9.3		6.4	6.0	4.5	7.4	10.4	6.3	7.7	6.6	5.9	7.8	7.1	7.6	4.2	4.8	3.8
Filling	7.7	8.1	10.7		4.8	4.9	4.1	5.2	8.4	4.8	5.5	5.6	6.2	5.8	7.1	4.3	7.6	5.2	4.9
Elmendorf, Warp	10.9	11.7	11.5		7.9	7.9	5.5	7.9	12.3	7.1	8.0	7.6	6.7	8.6	7.7	8.2	5.7	6.0	5.9
Filling	12.0	9.4	12.6		6.8	6.2	6.3	6.5	9.2	7.6	6.4	8.4	7.7	9.2	8.7	6.1	10.2	7.7	7.5
Bursting, Strength																			
Mullen, psi	345	311	340		283	284	287	289	348	298	266	282	314	256	402	267	318	260	315
Ball, lb.	249	264	271		219	175	213	199	237	227	177	263	226	208	302	177	210	219	178
Stiffness, 0.001 lb.																			
Warp	3.1	3.5	4.1		4.4	4.9	3.7	3.5	4.7	10.6	5.7	4.3	6.1	3.6	10.2	8.1	4.3	3.2	3.8
Filling	3.6	3.7	2.1		3.1	4.4	4.4	2.6	2.7	6.5	2.9	3.5	3.8	2.2	7.9	4.7	4.4	2.5	3.6
Thickness, 0.001 in., 3.63 psi	26.4	27.4	26.5		23.3	23.6	19.5	20.6	29.1	22.6	24.8	23.6	22.4	21.6	25.6	23.3	22.9	20.7	19.5
Camp Lee, Wear Score																			
9th cycle - Trousers	8.3	4.9	5.0		33.2	26.1	40.2	29.6	14.5	51.3	56.0	61.2	54.4	67.3	20.8	16.0	29.1	31.3	
Standard Control HBT - W.S.	18.0				40.3					47.4					23.0				